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Cooperative Multi-Channel Wireless Networks and Their Applications

Thesis submitted in partial fulfillment of the requirements for the award of *Doctor of Philosophy*

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Declaration

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Doctor of Philosophy, is entirely my own work and has not been taken from the work of others save to the extent that such work has been cited and acknowledged within the text of my work.

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Abstract

Growing popularity of wireless networks calls for their continuous evolution and improvement. Wireless devices are expected to be constantly decreasing in size and price. Meanwhile applications and services provided via wireless networks are expected to increase in popularity. We envision a Future Wireless Network (FWN) to consist of a large amount of miniature inexpensive autonomous devices spread in various location (e.g. hospitals, hotels etc). Along with the miniature devices the FWN may incorporate a set of WiFi access points (AP) which provide users with local Internet access. This thesis addresses some of the challenges of the FWN design. We consider how a FWN should use its available resources to ensure their efficient utilization. We examine how the FWN should adapt to various load heterogeneities within the network. These heterogeneities may by inflicted, for example, by the activity of the users or the network layout. We consider the necessity of the FWN to exhibit a certain degree of flexibility that will allow the FWN to accustom to diverse requirements of possible application scenarios. And finally we consider how users should control and fine-tune the performance of the FWN.

Node cooperation serves as a foundation of autonomous wireless network design in general. The cooperation increases intelligence of the nodes, makes them more aware of each other's activities. Research presented in this thesis is divided into two parts. The first part considers cooperation between miniature devices of a FWN, where we address the FWN design challenges by applying explicit multi-channel node cooperation. In particular we focus on sensor environments for health-care applications, where the devices are equipped with only single half-duplex transceivers and could be either on-body (e.g. Body Sensor Networks) or environmental. The second part of the thesis considers the implicit cooperation between a WiFi AP and its users.

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Contents

Chapter 1

Introduction

1.1 Background and Motivation

In this section we provide the motivation and the background of the research presented in this thesis. We start with describing modern wireless networks (Section 1.1.1) and then the envisioned Future Wireless Networks (FWNs) (Section 1.1.2). Further we describe the existing wireless transmission technology that will, in our opinion, become the basis for the FWN design (Section 1.1.3), and finally we present the key challenges of the FWN design (Section 1.1.4).

1.1.1 Wireless Networks Today

The term *wireless network* refers to any network of nodes inter-connected by means other then cables of any kind. Typically nodes of such a network exchange data via radio signal transmission, where the nodes are equipped with specific transceiver devices to enable transmission/reception to be carried out. Wireless networks do not require complex wired infrastructure, and hence are relatively cheap and simple to be deployed. Deployment of wireless networks provides their end-users with wide-coverage opportunities to remain connected to the desired services at anytime, anywhere. This has resulted in an extensive growth of wireless networks over the recent years. For example, the application range of today's wireless networks stretches from catering for specific needs of single individuals (e.g. Wireless Personal Area Networks) to building high scale universal infrastructure networks (e.g. Wireless Mesh Networks). The growth has significantly increased both the number and the variety of services being provided to the users via wireless networks. Today, conducting file transfer, video and audio conferencing, gaming, e-mail access, web browsing are only some of the typical examples, whilst cases of multiple services of various types operating over the same network are rather common. The growth has also significantly expanded the typical areas and locations where modern wireless networks are commonly used. Thus, wireless networks have become another essential part of the every day reality and can be found not only in modern high-technology buildings, but also in common outdoor locations such as parks, camping sites etc.

1.1.2 Wireless Networks Tomorrow

Despite the recent advances, further development of wireless networks and their applications is constantly expected by the end-users. The wireless devices are expected to be ever reducing in size and price, whilst the variety and quality of applications and services provided to the users is expected to continue growing. Satisfying these expectations consequently increases the amount of wireless devices exploited by a regular user. Therefore, we envision a future wireless network (FWN) to consist of a large amount of miniature inexpensive devices spread everywhere at various locations (e.g. a hospital, a school, an office building). The devices may be of diverse types, stretching from highly-specialized sensors or gadgets to laptops, PDA devices. These devices will use wireless transmission technology that will enable their seamless information exchange. The devices will surround their users, forming wireless environments dedicated specifically to the needs of the users. Each of the devices will operate in an autonomous fashion, while completing certain tasks through cooperation with other devices. For example, providing users with an update on the weather conditions may require information from sensors that monitor outside temperature, wind and humidity. Therefore, cooperation will be required by the sensors to collect the data, and efficiently transmit it to the right end users in a timely fashion. In the literature, the wide deployment of devices in the environment and their interaction with users is known as Internet of Things. We also envision that along with the miniature devices the FWN may incorporate a set of WiFi access points (AP). These APs may be used, for example, to provide local Internet access to the users. Distinctive purpose of the APs segregates them from the rest of the FWN nodes.

The omnipresence, autonomy and self-sufficiency of the FWNs will make their usage extremely attractive for numerous application scenarios. For example, in a hospital its environmental safety monitoring system (e.g. pollen level, toxins, temperature etc) may be engineered as a FWN consisting of various environmental sensors. Thereby, a patient of the hospital may use the system to receive immediate updates on the environmental safety as well as to deliver updates on his/her current medical condition to the medical personnel. Another good example can be represented by systems of cost effective information dissemination amongst mobile nodes concentrated within specific locations. Thus, customers of a shopping center or a mall may receive information on special offers and discounts, and also request detailed information on some of the products. The future wireless world will also impact on social networking. In this scenario, members of the same community and similar interests may use a FWN to support their interaction that could also be of a multi-dimensional nature. One dimension could be interaction between the users through WiFi APs, while in parallel spontaneous interaction between the users and the surrounding sensor nodes could be performed.

1.1.3 Transmission Technology

Wireless transmission technology used by individual nodes of a FWN presents one of the key components of the overall network design. This technology specifies one-hop wireless transmission that supports information exchange between neighboring nodes. The technology describes a transceiver device operating in conjunction with a Media Access Control (MAC) protocol that governs the transceiver's usage. The protocol operates at the MAC sublayer of Data Link layer of the network protocol architecture. Wireless transmission technologies of various types have been proposed over the years in order to satisfy needs of diverse application scenarios. Thereby, transmission technologies that could be used for manufacturing miniature FWN devices are presented in the IEEE 802.11 and 802.15 standards. IEEE 802.11, broadly known as WiFi also presents the technology behind manufacturing of APs. This section presents a brief overview of the two standards, where we present their transceiver devices as well as the MAC protocols.

IEEE 802.11 as well as IEEE 802.15 standard supports the single half-duplex transceivers. These transceivers at any one time may be switched to only one of the specified channels, that could be used either for data transmission or reception, but not both simultaneously. Success of any data transmission depends on whether the strength of its radio signal at the receiver overcomes the radio noise in the channel. This signal strength fades with distance [1], while the maximal distance at which a successful reception is possible is called the transmission range.

Meanwhile, the signal also contributes to the radio noise for any other concurrent transmission conducted via the same channel. This contribution may lead to that transmission's corruption, which is commonly called *collision*. To avoid collisions nearby nodes schedule their transmissions, where the scheduling is performed by the MAC protocol.

IEEE 802.11 transceiver

The first IEEE standard for wireless networks, namely IEEE 802.11 was originally published in 1997 [2]. The standard focuses on providing wireless connectivity for fixed, portable, and moving stations within a local area. The original standard describes a half-duplex transceiver that operates in 2.4GHz frequency band. The transceiver is able to carry out data transmission at rates of 1 and 2Mbps using Direct-Sequence Spread Spectrum (DSSS) and Frequency-Hopping Spread Spectrum (FHSS) modulation techniques. The indoor and outdoor transmission ranges of the transceiver are 20 and 100m correspondingly. As an alternative technology for the transceiver, the standard also presents diffused infrared transmissions that can be carried at the rate of 1Mbps. Since launching the standard, a number of updates by a series of amendments that target improving specific aspects of the wireless network operation have been proposed. These amendments may differ from one another (e.g. modulation technique, frequency band), and may be even categorized as different technologies (e.g. IEEE 802.11a, IEEE 802.11b networks).

IEEE 802.11a [3] describes operation in 5GHz frequency band, where the transmission rates can be up to 54Mbps, with 12 non-overlapping channels. Any of the channels can be used for transmission, where each channel uses Orthogonal Frequency - Division Multiplexing (OFDM) modulation technique. The technology increased the indoor and outdoor transmission ranges to up to 35 and 120m correspondingly. Meanwhile, IEEE 802.11b [4] remains in the same 2.4GHz frequency band and allows transmission at rates up to 11Mbps through any of 14 non-overlapping channels. The performance improvement of this technology is achieved by extending the DSSS modulation technique of the original standard. Further IEEE 802.11g enhancement [5], allows transmission at rates up to 54Mbps for 2.4GHz frequency band through using the OFDM modulation technique.

Most recent amendments to the IEEE 802.11 standard provide even further performance improvement. However, the improvement is achieved via increasing energy-expenditure and coast of the transceiver. This makes the technologies of these amendments inapplicable to the FWN design. Thus, IEEE 802.11y [6] increased the outdoor transmission range (became 5000m) via increased power transmission in 3.7GHz frequency band. IEEE 802.11n [7] increased physical transmission rates (became up to 600Mbps) in both 2.4 and 5GHz frequency bands through using multiple-input and multiple-output antennas, which are of higher complexity/price.

IEEE 802.15 transceiver

Another type of wireless transceivers is described by the IEEE 802.15 standard. The standard targets Wireless Personal Area Networks (WPAN), which are normally used for information collection over relatively short distances within personal space of a single individual. The standard assumes each network node to be equipped with a half-duplex transceiver that is able to transmit at very low power over relatively short distances. In comparison to the previously described IEEE 802.11 standard, the technology differs within IEEE 802.15 standard by clauses rather than amendments.

IEEE 802.15.3 [8] supports WPANs that are dedicated for high-rate, low-power, and low-cost multimedia communication within 2.4GHz frequency band, where the transmission rates reach up to 55Mbps via a total of 5 wireless channels. On the other hand IEEE 802.15.4 [9] specifies WPANs that are dedicated for low-rate, low-power, and low-cost communication within the same 2.4GHz, where the typical transmission rate is 0.2Mbps. Finally, IEEE 802.15.6 [10] specifies low-power wireless transmissions within on-body/implanted monitoring networks and supports transmission at rates up to 10Mbps. The clause proposes a number of channels available for transmission, where some of the channels reside within 2.4GHz frequency band.

MAC protocol

Both IEEE 802.11 and IEEE 802.15 standards, each technology uses the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism in order to support autonomous networking. The mechanism coordinates usage of one channel by multiple nodes, where the coordination represents a technique of implicit cooperation between neighboring nodes. Each node immediately prior to transmitting verifies (carrier sensing) that no concurrent transmissions of other nodes are present and may be harmed by the transmission of the node. In case such a transmission exists, the node delays its transmission. Additionally, the CSMA/CA includes a random back-off mechanism that provides neighbors of the node with a possibility to accomplish their transmissions prior to its own. The CSMA/CA reduces the number of collisions that transmissions of network nodes suffer in total. However collisions still remain possible. For that reason each technology complements the mechanism with an acknowledgment process that for each transmission confirms the success. Failure of the acknowledgment process leads to a retransmission. Other extensions for the CSMA/CA mechanism are also presented in the standards in order to tailor their performance for particular application scenarios. For example, IEEE 802.11b [4] technology supplies the RTS/CTS mechanism that reduces influence of collisions which involve transmissions of large data packets. IEEE 802.11e [11] technology provides a priority mechanism that distinguishes diverse quality of service requirements to wireless network performance from services of different nature.

1.1.4 Challenges

While the previous section has presented an overview of tremendous achievements in transmission technology of wireless devices, the current state of the art is still far from the requirements of the FWNs. We envision that features of the FWNs include autonomy and self-sufficiency, which in turn will result in their rapid deployment to market and fuel further growth of wireless devices. However, these features also pose certain challenges to the FWN design, where the challenges considered by this research are presented in this section. The challenges are presented in relation to the above example of a patient in a hospital environment. However, relevance of the challenges is not limited exclusively by the example, and remains significant for various other uses of the FWNs.

C1. Efficiency

Design of the FWNs should explore possibilities not only to extend the capacity of the wireless networks (e.g. using equipment of higher complexity and sophistication), but also to use the already available transmission resources in a more efficient and effective way. Therefore, the design should maximize the capacity of the FWN. For instance, in the patient monitoring example, the maximum capacity could support the maximum number of patients simultaneously.

C2. Adaptivity

FWNs are subject to encounter heterogeneities of various kinds. For example, in a hospital environment certain locations (e.g. canteens, waiting areas, cafeterias etc.) may experience higher concentrations of patients that use Body Area Networks to deliver their health-condition updates. Also the environmental sensors of the monitoring system itself may be unevenly distributed within the hospital area. Certain heterogeneities may be caused by inequality of environmental monitoring traffic generated by sensors of different nature. Such a heterogeneity may result in overloading certain parts of the FWM and, hence, impact abilities of these devices to forward data efficiently. Even though, various heterogeneities may appear within a FWN due to the heterogeneity of its actual nodes (e.g. different node-capacities, processing powers, Operating Systems), in this thesis we concentrate only on load heterogeneities that appear within FWNs of homogeneous nodes. Therefore, the design needs to incorporate a technique that will improve performance of the FWN by adapting to any load heterogeneity.

C3. Flexibility

Various scenarios of FWN usage may pose their own specific requirements to the performance of the network. For instance, coming back to the health-monitoring example the FWN is required to ensure maximal delivery of packets with health information of the patients, while packets of patients in more severe conditions should by prioritized. Contrary to that a system of information dissemination in a shopping center may elect energy-efficiency of the FWN nodes over packet delivery ratio. Furthermore, co-existence of different traffic classes results in diverse performance requirements within the same application scenario. Therefore, the FWN design is required to exhibit a certain degree of flexibility to cater for a wide variety of application scenarios and their traffic classes.

C4. User-control and fine-tuning

Requirements to the performance of a FWN may evolve and alter in time. In order to account for that the FWNs are required to be brought closer to their users. Hence, the users should be provided with an ability to influence the FWN performance. Therefore, the FWN design is required to make feasible end-to-end user-control and fine-tuning of the performance of the network. For instance, for the health-monitoring example, such a control may provide the ability for medical officers to set and/or configure their requirements that improve the patient monitoring process. Also the medical officers should be given an ability to configure the FWN if the quality of the patient-monitoring data is below standard.

1.2 Research Scope of The Thesis

This section discusses the scope of the research presented in this thesis. Section 1.2.1 presents the limitations of current wireless networks which are the focus of this thesis. Section 1.2.2 discusses the main objectives of the research, which are represented in the form of Research Questions. In this thesis our work is subdivided into two parts. The first part of the thesis concentrates on developing a cooperative solution for miniature FWN devices to support efficient multi-channel transmission. In particular, we focus on patient-monitoring sensor devices and their health-care applications. In this part of the thesis we consider two particular types of node-cooperation. Cooperation at the MAC layer insures efficient asynchronous dynamic channel allocation between the FWN nodes, while cooperation at the Network layer insures adaptability of the data-delivery routes within the FWN. The second part concentrates on design issues of autonomous wireless APs incorporated into a FWN. In particular, we focus on the scenario of FWN users communicating to an AP node. We consider optimization of the CSMA/CA mechanism through modeling delay and transmission energy metrics for wireless nodes. The two parts of the research work are titled as follows:

- **P1. Cooperation of miniature devices;**
- **P2. WiFi AP modeling.**

1.2.1 The Limitations

Cooperation of miniature devices. Size, price and energy limitations that apply to miniature FWN devices pose a significant restriction to their equipment. Thus, equipment of a miniature device is represented by a singe half-duplex transceiver (either IEEE 802.11 or IEEE 802.15) and cannot be extended in order to improve performance of the device. Therefore, any performance improvement may be achieved only by increasing intelligence of the nodes, making them more aware of each other's activities. The improvement requires further development of algorithms and protocols of the FWN architecture. This part of the thesis considers the following limitations:

- **Single-channel at the MAC layer:** MAC cooperation (the implicit cooperation of the CSMA/CA mechanism (Section 1.1.3)) is limited to the use of only a single channel for transmission. Consequently, all miniature devices of a FWN are forced to use the same channel, while a number of remaining free channels are available. This, in turn, becomes a potential bottleneck especially for the cases of high node density. Meanwhile, this issue can be resolved through extending the MAC cooperation in a way that will allow nodes to use multiple channels for their transmissions. Such an extension will allow neighboring nodes to transmit in parallel and increase capacity of the FWN. This limitation also correlates with the challenge ***C1 (Efficiency)*** of the FWN design.

- **Low awareness of traffic heterogeneity:** Meanwhile, cooperation between nodes of a wireless network does not end at the MAC layer. The cooperation stretches further to the Network layer also, where it supports packet routing. Often deployment irregularity and great number of nodes of a wireless network do not allow each node to be equipped with sufficient routing information. This information is derived from cooperation between the network node. For example, popular AODV routing protocol [12][13] presents a cooperative technique for establishing routes of minimal length. However, standard routing techniques (e.g. AODV) do not consider traffic load heterogeneity across the network. This leads to some of the delivery routes going via highly loaded network regions, which significantly degrade performance of these routes. This limitation also correlates with the challenge ***C2 (Adaptivity)*** of the FWN design.

- **Lack of flexibility and feasibility for user-control and fine-tuning:** Low level (e.g. MAC, Network layers) technical configuration details of a wireless network lay typically beyond the knowledge available to its end-users. Examples of such technical details include Back-Off Window Size of the CSMA/CA mechanism, Time To Live of the AODV protocol and others. Improving network performance via re-configuring these parameters during runtime is a highly challenging task that is commonly worth a research study. Therefore, modern wireless systems commonly use fixed preset low-level network configurations (e.g. health-monitoring [14][15]). This significantly restricts flexibility of these systems and impacts their feasibility for user control and fine-tuning. This limitation also correlates with the challenges ***C3 (Flexibility)*** and ***C4 (User-control and fine-tuning)*** of the FWN design.

WiFi AP modeling: WiFi AP nodes are commonly used to deliver a large variety of services to their end users. Certain of these services are rather sensitive to the quality of service provided by the wireless connection, where examples of such services include audio and video conferencing, on-line gaming and others. Requirements of such services may include throughput guarantees, delay guarantees and other. Recent growth of interest for Green Energy-efficient ICT will require additional consideration of energy-related guarantees. However, performance of a WiFi AP is regulated by the CSMA/CA mechanism that is rather complex to configure and fine-tune. Further more, predicting performance of any of the typical configurations provided in appropriate standards proves to be a task of significant complexity. This study develops an analytical model for the CSMA/CA mechanism to enable its comprehensive analysis. The model will significantly simplify the process of configuring and fine-tuning of a WiFi AP. The model will simplify addressing the challenges ***C1 - C4*** of the FWN design.

1.2.2 The Objectives

Cooperation of miniature devices: Research presented in the first part of the thesis explores possibility to extend node cooperation between FWN nodes in such a way that will address the limitation presented in the previous section and the design challenges presented in Section 1.1.4. In order to do so we extend cooperation of wireless network nodes at the MAC and Network layers. The objectives of the first part of the study are represented by the following Research Questions (RQ):

- ***P1-RQ1. Multi-channel MAC cooperation:*** *How should node cooperation* *at the MAC layer be established in order to provide efficient multi-channel transmission?* ***(challenge C1)***

- ***P1-RQ2. Adaptive routing:*** *How should nodes of a FWN cooperate at the Network layer in order to adapt to various load heterogeneities?* ***(challenge C2)***

- ***P1-RQ3. Flexibility:*** *What are the side-effects of the proposed cooperation with regards to the FWN performance? In what way should the cooperation be managed in order to achieve a reasonable balance between the performance improvements and the side-effects?* ***(challenge C3)***

- ***P1-RQ4. User-control and fine-tuning:*** *What mechanisms should be integrated into the architecture of the FWNs to allow user-control and fine-tuning of the cooperation?* ***(challenge C4)***

WiFi AP modeling: Research presented in the second part of the thesis explores possibility of building an analytical model that will allow precise performance estimation of delay and energy guarantees of the CSMA/CA mechanism. The objectives of the second part of the research are represented by the following Research Question (RQ):

- ***P2-RQ1. CSMA/CA modeling:*** *How could the CSMA/CA mechanism be modeled in order to predict quality of service (delay guarantees) as well as energy efficiency of a WiFi AP?* ***(challenges C1 - C4)***

1.3 The Approach

In this section we describe the research approach that has been developed to answer the research questions. The research questions are addressed sequentially. Each research question is addressed based on the findings of the previous questions. A separate subsection describes the method that has been selected to validate the findings of the research questions.

1.3.1 Cooperation of miniature devices

P1-RQ1. Multi-channel MAC cooperation: Chapter 2 presents an overview of previously proposed solutions, which are organized into three separate categories. However, solution of only one category, namely the Dedicated Control Channel (DCC) category could be used for FWNs. The study considers the most advance state-of-the-art DCC MAC cooperative protocol, namely Cooperative Asynchronous Multichannel MAC (CAM-MAC) [16][17]. To the best of our knowledge, CAM-MAC presents the most advanced technique of MAC cooperation that describes an autonomous process of node negotiation. In this thesis, we have extended CAM-MAC to infer the topology and surrounding environmental condition, in order to further maximize the capacity of the overall network. This includes cooperative topology inferencing technique that increases awareness of the network nodes of activities within their surroundings.

P1-RQ2. Adaptive routing: Various load heterogeneities also quite commonly appear and obstruct efficient data delivery in the case of conventional wired networks. Such obstructions are commonly countered by modern routing protocols, which incorporate various techniques of data delivery adaptation. Thus, Balasubramaniam et al. [18][19][20] present the Gradient Routing technique. The technique uses node cooperation to create a gradient field within the network, where the field leads the adaptive data delivery. The technique has been thoroughly investigated for the case of wired networks. In this study we consider adapting the Gradient

Routing technique for the case of multi-channel FWNs.

P1-RQ3. Flexibility: Node cooperation of the Gradient Routing techniques allows data delivery to be performed in a way that avoids highly loaded regions of the network. However, in order to avoid these regions some of the delivery routes are diverted from their shortest paths. Meanwhile, how far a route may be diverted from the shortest path is governed by the γ-parameter of the Gradient Routing technique. The study considers the influence of the γ-parameter on the overall FWN performance. This allows us to evaluate the side-effects of the proposed cooperative solution. For the evaluation purposes we use performance metrics of three types that describe (1) conventional network performance, (2) network adaptivity, and (3) MAC layer cooperation correspondingly. These metrics enable us to understand the influence of the γ-parameter on the performance of the network at various architectural levels.

To assess flexibility of the proposed cooperation, the study considers the possibility of existence of a number of different traffic classes within the same application scenario. We consider utilizing different γ-values for different traffic classes. Consequently, we consider whether performance of a FWN may be improved via a run-time modification of its γ-parameters. Such a modification must be accomplished in close consideration of an application scenario. We consider remote health-monitoring of a patient in a hospital environment, where patient-monitoring data is delivered to a remote competence center and brought to the attention of medical personnel via a set of environmental sensors forming a FWN. Appearance of the patients within the hospital may cause load heterogeneity across the FWN as they may gather at various locations, points of interest.

P1-RQ4. User-control and fine-tuning: Similarly to *RQ4*, this question is considered in the scope of the remote health-monitoring in a hospital environment. We develop an architecture that provides users with the end-to-end control of the FWN. The architecture allows medical personnel to influence patient monitoring through a set of high level policies. The policies specify run-time γ-parameter modifications as well as possible modifications of the patient monitoring.

1.3.2 WiFi AP modeling

P2-RQ1. CSMA/CA modeling: We consider the case when all users of a WiFi AP are located only one hop away and, therefore, are able to communicate directly to the AP. Traffic is directed from the users towards the AP, where for each user the packet arrival process is Poisson. We consider the wireless network to operate in perfect physical-channel conditions. In this case performance of the network is influenced by the users and their network load. Thus, with an increase of either of the parameters both delay and energy consumption of the user devices increase. Quite commonly QoS requirement of a service delivered via an AP formulate restrictions to the overall packet delay (delay guarantee) where a certain percentage of the packets is expected to be delivered within a predefined timeout. To estimate this probability we estimate delay distribution for a generic transmission of a wireless node (a user or the AP). Similarly, to estimate energy efficiency we estimate transmission-energy distribution for a generic transmission of a wireless node. These two distributions provide a sufficient insight into the internal structure of the packet delay and transmission energy metrics. Such an insight is highly beneficial for modeling performance of a wireless node, for example, as a M/G/1 queue (see Brandwajn and Begin [21] for the effects of higher-order service-time distribution properties).

1.3.3 Validation

In order to validate the findings of both parts (P1 and P2) of the thesis, simulation work has been conducted on our custom-developed Java based event driven simulator. The simulator includes models for the mechanisms and protocols developed during the research. In order to insure accuracy of the results obtained from the simulator the bottom-to-top development approach has been selected. Hence, the development started with the implementation of the propagation media and followed on to the further layers of the Network Architecture. Each stage of the development process has been validated using a set of appropriate JUnit tests, which insure integrity and correctness of the overall process. Additionally, our research presented in [22] and [23] shows good agreement between results obtained from the simulator and results of analytical modeling. This confirms the high precision of our custom-developed simulator. The simulator allows each network node to be equipped with only a single half-duplex transceiver. The transceiver can be accustomed to satisfy specifications of either IEEE 802.11 or IEEE 802.15 standard. The simulator uses the spherical model of wireless signal propagation. The transmission may be successfully received only by another node located within the transmission range of the transmitter. The reception is successful if and only if for the entire transmission's duration the receiver and the transmitter have been tuned to the same channel, and the receiver is not in the transmission range of any other node attempting a concurrent transmission through that same channel. Even though the model presents a simplified approximation of the actual signal propagation, the model provides a realistic estimation and, therefore, is quite commonly used by similar research studies (e.g. [16][17]).

Findings of the P2-RQ1 are also validated via series of NS-3 [24] simulation. NS-3 simulator is used for validating our proposed model for the CSMA/CA mechanism. NS-3 is a broadly-known simulation-tool that is commonly used for the CSMA/CA modeling. Therefore, using NS-3 for validation purposes improves credibility of the research.

1.4 The Contribution

We believe our thesis makes significant contribution towards engineering cooperative multi-channel wireless networks. This section summarizes the main achievements of the research of the thesis. The achievements of each part (P1 and P2) are presented below, while Tab. 1.1 and Tab. 1.2 map the achievements to the Research Questions that they address and research papers that serve as the output of this research.

1.4.1 Cooperation of miniature devices

P1-RQ1. Multi-channel MAC cooperation:

- **A1.** We have identified the Redundant Channel Blocking (RCB) problem [25] found for single transceiver sensor devices. The problem results from a drawback of node cooperation that provides utilization of the available data channels at the MAC layer. The problem reduces the overall throughput of the network.

- **A2.** We have developed the distributed mechanism of Virtual Topology Inferencing [25]. The mechanism significantly reduces influence of the RCB problem, and improves thorough performance of the sensor network.

P1-RQ2. Adaptive routing:

- **A3.** The research has developed a cross-layered MAC&Network layer protocol [26] for single transceiver device by integrating the CAM-MAC-ARCB and

Table 1.1: P1. Research Achievements

Res. Question	Challenge	Achievement	Presented in Papers	Appx.
P1-RQ1	C1	A1, A2	IEEE CoCoNet2 2009 [25]	A
P1-RQ2	C2	A3	IEEE AINA 2010 [26]	B
P1-RQ3	C3	A4	IEEE AINA 2010 [26]	B
			IEEE TCE 2012 [27]	C
			IEEE TBME 2012 [28]	D
		A5	IEEE TCE 2012 [27]	C
		A5, A6	IEEE TBME 2012 [28]	D
P1-RQ4	C4	A7, A8	IEEE TBME 2012 [28]	D

the PGBR Gradient Based Routing. This new routing protocol allows paths to be discovered around loaded areas of the network.

P1-RQ3. Flexibility:

- **A4.** We have thoroughly analyzed the influence that the delivery route adaptation has on the overall network performance. The influence is considered with respect to configuring the parameter of the Gradient Routing protocol. The analysis considers the following network performance metrics: packet delivery ratio [26][27][28] (type (1)), node energy consumption [27][28] (type (1)), RCB rate [26] (type (3)), load balance[27] (type (2)), hop count [26][27] (type (2)), MAC layer negotiation rate[27] (type (3)), routing capacity of the network nodes [26] (type (2)). In [27][28] we have also presented evaluation of the solution for the remote health-monitoring in a hospital, where patient-monitoring data is delivered to a remote competence center and brought to the attention of medical personnel via a set of environmental sensors forming a FWN. Appearance of the patients within the hospital may cause load heterogeneity across the FWN as they may gather at various locations, points of interest. The evaluation has shown that the adaptation improves performance of the network in terms of packet delivery ratio (improved delivery reliability) due to better load balancing across the network. However, the adaptation also increases the length of packet delivery routes (higher hop-count), energy consumption of the nodes, and their necessity for MAC layer cooperation, which become the price for the reliability improvement.

- **A5.** We have considered existence of three traffic classes for the remote health-monitoring in a hospital. The classes correspond to patients in *Stable*, *Urgent* and *Critical* conditions. The classes are ranked 0, 1 and 2 correspondingly. The ranking reflects on the importance of the on-time information delivery for the classes. For the different classes we have proposed a way for service differentiation that translates to different parameters of the gradient routing [27][28]. Traffic of higher class uses higher parameter values in order to insure higher reliability.

- **A6.** We have shown that performance quality improvement for a group of services may be achieved during runtime by modifying the gradient routing parameters with heterogeneous values [28].

P1-RQ4. User-control and fine-tuning:

- **A7.** For the considered health-monitoring scenario we have proposed a new metric called QoHM [28] that allows medical officers to provide feedback on the quality of sensor readings delivered through the network. The metric describes effect that packet losses have on traffic of various reliability levels (0-2 ranks).

- **A8.** We have proposed a hierarchy of high-level policies that allow medical officers to influence performance of the sensor network operating within the hospital [28]. The policy hierarchy can configure the gradient routing parameter as well as reduce the network traffic of low priority class, where conflicts between the policies are identified and resolved by a specific policy-engine prior to their deployment.

1.4.2 WiFi AP modeling

Table 1.2: P2. Research Achievements

Res. Question	Challenge	Achievement	Presented in Papers	Appx.
P2-RQ1	C1 - C4	A9, A10	IEEE ISCC 2010 [22]	E
		A9, A10	IEEE ISCC 2011 [23]	F
		A9, A11	Under review [29]	G

P2-RQ1. CSMA/CA modeling:

- **A9.** For the CSMA/CA mechanism we have analyzed the internal structure of the following performance metrics: packet delay [22][23] and transmission energy [29]. The event-based (also interval-based in earlier works) representations for the two metrics have been proposed.

- **A10.** For the case of network traffic saturation we have highlighted the exponential nature of the CSMA/CA packet delay [23]. Also for this case we have investigated the dependency between the sizes of transmitted packets and the two following network performance metrics: throughput, delay [22].

- **A11.** We have developed a random sum model for the packet delay and transmission energy metrics for the case of non-saturated traffic [29]. The model allows to estimate numerical distributions for each of the two metrics as well as their joint distribution. Analysis of the model shows a clear dependence between values of the two metrics.

1.4.3 Publications

The results of the research have been documented in a number of research articles. The complete list of the articles is presented in Chapter 4. Articles related to the first part of the thesis include 4 peer-reviewed publications. Two of the articles have been published in journals, namely *IEEE Transactions on Biomedical Engineering* (**(AR<16%)**) and *IEEE Transaction on Consumer Electronics*. One article has been presented at a conference, namely *IEEE International Conference on Advanced Information Networking and Applications* (IEEE AINA 2010). One of the papers have been presented at the *IEEE Cooperative and Cognitive Mobile Networks* (IEEE CoCoNet2 2009) workshop. Articles related to the second part of the thesis include 3 papers. Two of the papers have been presented at the *IEEE Symposium on Computers and Communications* (ISCC 2010, 2011). One paper is currently under a peer-review process.

Chapter 2

State of the Art

This chapter presents the state-of-the-art solutions that address problems considered by the research. The solutions are divided into two subsections. Section 2.1 presents state-of-the-art cooperative solutions for miniature FWN devices. Section 2.2 describes state-of-the-art analytical models for the CSMA/CA mechanism.

2.1 Cooperation of miniature devices

In Section 2.1.1 and 2.1.2 we present state-of-the-art solutions dedicated to improving performance of wireless networks by extending cooperation between their nodes, where Section 2.1.1 presents multi-channel cooperative MAC protocols and Section 2.1.2 presents state-of-the-art adaptive routing protocols. Meanwhile, Section 2.1.3 presents overview of the state-of-the-art Health-Care solutions that use devices equivalent to the considered.

2.1.1 Multi-channel MAC cooperation

Due to the strict equipment limitations of the miniature FWN devices, in this section we only consider solutions which govern usage of a single half-duplex transceiver.

These transceivers at any one time may be switched to only one of the specified channels, that could be used either for data transmission or reception, but not both simultaneously. Mo et al. [30] presented a comprehensive classification of the existing cooperative MAC protocols that have been proposed to allow multi-channel transmission. The classification was further added by Wang et al. [31] and Soule De Castro et al. [32] with protocols that appeared after the original publication. The classification separates the solutions into the three categories presented below.

Time Division

Fragment-based representation of network operational time serves as the common ground that unites the Time Division cooperative protocols. So, operational time of a network is considered as a sequence of separate fragments, whereas each fragment is divided into one control and a number of data frames. Each control frame is used by the network nodes to schedule their use of the available physical channels during the data frames of the same fragment. In such a way, control frames encapsulate cooperation between the network nodes. The cooperation represents a packet exchange process within a sender-receiver pair, where the packet exchange is often carried out through one dedicated channel and guarded by the CSMA/CA mechanism. During the cooperation, the sender and its receiver exchange information (data frame and transmission channel) on their transmission. Neighboring nodes observe cooperation of the pair, and this allows them to avoid using the same data channel during the same data frame. Examples of Time Division solutions can be found in [33][34]. Meanwhile, the necessity for a wireless node to share each control frame with its entire neighborhood turns into a bottleneck in case of networks of high node density. This is considered in a number of research studies [35][36][37][38] which investigate approaches to reduce influence of this drawback.

However, appearance of this drawback makes such cooperative techniques unsuitable for miniature FWN devices.

Channel Hopping

Protocols of the Channel Hopping category imply cooperation of one specific form that stands out due to its unique design. Thus, in order to avail to the use of a number of data channel, wireless nodes continuously switch between the channels. At each channel, nodes remain for a certain time period that allows only a single sender-receiver pair to establish a transmission. The transmission is established via a packet exchange process guarded by the CSMA/CA mechanism. The process relates only to the usage of the current physical channel, and is somehow similar to an ordinary single-channel transmission of data. The sender-receiver pair that has established the transmission performs its execution through the current channel, while the rest of the nodes continue the switching process. Once the transmission is over the pair resumes the switching process. Therefore, a number of concurrent transmission via different channels may be established. Thus, [39], [40] and [41] present cooperative protocols where all network nodes must follow a universal sequence of channel-hopping in a tight synchronous manner. To relax the synchronization requirement techniques that use node-specific sequences are proposed in [42], [43] and [44]. Further research presented in [45], [46], [47] and [48] proposes techniques that adapt the hopping-sequences to condition diversity of the physical channels, and thus favor utilization of the better channels. However, the channel-hopping techniques require a rather high level of synchronization between network nodes and suffer quite sufficiently from its absence. At the same time, this synchronization requirement contradicts with the high autonomy of the FWN nodes, and consequently makes the channel-hopping techniques inapplicable for the miniature

FWN devices.

Dedicated Control Channel

The Dedicated Control Channel (DCC) category unites the protocols that use a specific dedicated channel, where the network nodes schedule their upcoming transmissions in a cooperative fashion. The transmissions are carried out via the remaining channels, which are also called as “the data channels”. The DCC solutions do not use the fragment-based representation of the network operational time, and this distinguishes them from the Time Division solutions. Therefore, a sender-receiver pair may attempt to schedule a transmission at any time. The scheduling represents a packet exchange between the sender, its receiver and sometime their neighbors. The packet exchange is guarded by the CSMA/CA mechanism. The packet exchange include all necessary particulars of the transmission including its starting time, duration and data channel. The main goal of the packet exchange is to inform neighbors of the sender and the receiver of the transmission, so the neighbors will avoid using the same channel during the same time. However, as the network nodes are equipped with only a single half-duplex transceiver, the nodes miss cooperation of their neighbors while transmitting through the data channels. This leads to nodes having incomplete knowledge about transmissions of their neighbors. This incomplete knowledge increases possibility of collision between data transmissions. Various solutions to encounter such drawbacks can be found in [49][50][51][52][53][54][55]. However, these solutions either require additional equipment for the nodes (e.g. [49] requires additional transceiver), or reduce efficiency of the data channel utilization (e.g. [51] artificially delays some of the co-operations). Meanwhile, one solution that does not have any of the two drawbacks is presented by Luo et al [16]. The proposed cooperative technique (Cooperative

Asynchronous Multichannel MAC (CAM-MAC) protocol) relies on the data channel utilization knowledge collected by a neighborhood rather than by individual nodes. The technique is further generalized by the same authors as Distributed Information SHaring (DISH) [17][56][57]. Energy efficiency of the DISH was further considered in [58][59]. CAM-MAC protocol and DISH represent a novel cooperative asynchronous technique that allows multi-channel transmission and has a tremendous potential for FWNs. However, the technique can lead to "Redundant channel blocking" that affects efficiency of the data channel utilization. In this study we identify the problem and provide its detailed description. We also provide a cooperative technique that allows mitigating appearance of the problem and its influence on the overall network performance.

2.1.2 Adaptive Routing

Commonly adaptation of a wireless network to its load heterogeneities is covered by mechanisms and protocols of packet routing. This section provides an overview of such techniques and protocols recently proposed by the research community.

Opportunistic Routing

Opportunistic routing solutions present one of the popular approaches that have been actively developed over the recent years to support the required network adaptivity (e.g. [60][61][62][63][64][65][66][67]). An overall description of the approach and a survey of some solutions is presented in [68]. The approach relies on the ability of a node forwarding (the forwarder) a packet to estimate probabilities to deliver the packet to its destination for other network nodes located within reach of the forwarder. These probabilities may take into account various parameters of the current state of the network including connection reliability (e.g. due to external influence), load balancing [61], etc. The forwarder propagates the packet further to a subset of nodes, where the subset is identified with respect to the probabilities. Each node of the subset further becomes a forwarder for the packet. Forwarding the packet via the node subset increases chances of the packet to be successfully delivered to the destination. Meanwhile constructing the subset with respect to the probabilities leads to adaptivity. Thus, nodes of an overloaded network regions have lower potential for data delivery and, therefore, are distinguished by lower probability values. Consequently selecting nodes of higher probability values will divert packets from such network regions. Several studies have been dedicated to understanding potential gains of the approach though its analytical modeling. For example, [69] shows that in some network configurations the approach may improve the delivery ratio up to 3 times. However, the approach requires each network node to maintain a complex network overview (e.g. the delivery probabilities) that might be of a rather substantial size. Also, delivery probability estimation presents a complex task. This significantly restricts the applicability of the approach for FWNs.

Intelligence-Based Routing

Adaptive routing represents an optimization problem that considers achieving either maximal or minimal value for a certain metric. This metric describes performance of the wireless network and relates to the end goal of the adaptation. For example, load balancing across a wireless network may be considered through the following metric:

$$Network\ Balancing \;=\; \frac{\left(\sum_i x_i\right)^2}{N \cdot \sum_i x_i^2},$$

where N denotes the total number of the network nodes, and x_i is the overall number of packet forwarded by node i. Meanwhile, Artificial Intelligence (AI) provides a variety of techniques that allow solving such problems. Therefore, various solutions have relied on AI to improve routing.

For example, [70][71][72][73][74][75] present protocols based on Ant Colony Optimization technique. To establish a route between nodes A and B the protocol mimics behavior of an ant colony that searches for food. The colony and the food are located at nodes A and B correspondingly. Therefore, route discovery packets imitate behavior of ants searching for food, where the process will converge to a specific path.

Research work developed in [76][77][78][79] present protocols based on Genetic programming. The solutions optimize performance of the wireless network through a continuous genetic-based evolution of it current network routes, which are initially established based on a heuristic of a particular type (e.g. path-length heuristic). The routes evolve in accordance with the genetic-operations of mutation and crossover specified by the solution. Routes formed during the evolution go through a process of natural selection that eliminates the furthest away from the optimum. Closeness to the optimum is identified by the fitness function specified by the solution.

AI techniques often require to go through a number of consecutive iterations in order to converge to a result that is sufficiently close to the optimum. The convergence may take a relatively long period of time, and hence is not applicable for short data-exchange routing. Therefore, intelligence-based solutions are mostly utilized for multi-media routing (e.g. [73][75]) or mesh-networking (e.g. [77][74]), where dynamics of the network do not change quickly. Additionally, intelligence-based solutions require nodes to maintain information regarding previous iterations of the technique (e.g. ant-pheromone strength, genomes of the current population). This information may be substantial in size. The reasons presented in this paragraph reduce applicability of the Intelligence-based solutions for the miniature FWN devices.

Heuristic Routing

Heuristic protocols present an independent routing approach that is very popular for wireless networks in general. Each protocol of the group is built with respect to a specific delivery-route heuristic. For a sender-receiver pair the protocol selects the packet delivery route with the best value of the heuristic. For example, [13][12] present AODV wireless routing protocol that uses the path-length heuristic. AODV is one of the first protocols proposed for wireless networks. Since its first introduction the protocol has become a popular choice for modern wireless network. For a new sender-receiver pair AODV starts a hop-by-hop route-discovery process. The process returns a number of possible routes, where the one with the least path-length is selected. However, AODV routing does not take into consideration any other information in relation to the routes. This significantly restricts the adaptability of the protocol. Therefore, certain approaches were proposed to encounter this problem. These approaches are presented in this section.

Recently a significant effort has been made to improve previously proposed Back-pressure adaptive routing [80][81][82][83][84]. Back-pressure routing technique relies on the algorithm originally proposed by Tassiulas and Ephremides [85] for multi-hop radio networks. The algorithm, in its turn, relies on concepts of Lyapunov drift from the Queuing Theory. The algorithm routes data towards its destination in order to maximize differential backlog (difference in number of packets awaiting delivery) between neighboring nodes. The original algorithm has not become the primary choice due to its poor delay performance and high implementation complexity. Even thought the recent development improves the delay performance of the algorithm, its still requires a rather complex implementation. Thus, each network node is required to maintain a separate packet buffer for each destination, whereas maintaining such buffers may not only require sufficient resources but also result in significant time overhead. This significantly reduces applicability of the approach for miniature FWN devices.

Another technique was proposed by Balasubramanian et al for the case of wired networks [18][19], namely the Gradient Routing Technique. The technique uses cooperation between nodes of a network to establish a gradient field within the network, whereas the field leads the adaptive data delivery. For a data flow of a source-destination pair the field's value at each node accounts for both the shortest path distance towards the destination and the availability of the node. Meanwhile, the field values represent a delivery-route heuristic that can be calculated autonomously, which simplifies implementation of the technique. The technique was compared to the conventional techniques [18][19] (e.g. shortest path routing) as well as one of the state-of-the-art Back-pressure routing solutions [20], where the Gradient Routing had shown the superior performance. The Gradient Routing technique shows a significant level of adaptivity and does not exhibit significant complexity of implementation. Therefore, in this thesis we select the Gradient Routing technique to develop an adaptive routing protocol for miniature FWN devices.

2.1.3 Health-Care Solutions

Health-care industry presents one of the possible areas where FWNs are envisioned to make a significant contribution. In particular, miniature FWN devices possess a tremendous opportunity for remote health-monitoring. Thus, a number of miniature devices belonging to one patient may form a Wireless Body Area Network (WBAN) that will continuously monitor condition of the patient without posing additional movement restrictions. Meanwhile, WBANs of different patients together with other FWN devices may be used for ad-hoc delivering of health-monitoring results to medical officers. Various WBAN health-monitoring systems have been developed over the recent years. For example, Malan et al [86] and Ko et al [87] considered emergency-related patient-monitoring. Kao et al [88] present a system for home-care patient monitoring, where the system also provides a real-time audio/video monitoring. Patel et al. [89] present a system for monitoring motor fluctuations in patients with Parkinson's disease. Vililba et al. [15] and Mougiakakou et al. [14] present a WBAN-based system for remote heart failure monitoring and type 1 diabetes correspondingly. Huang et al [90] present an architecture capable to incorporate heterogeneous health-monitoring sensors together with other mobile devices (laptops, mobile phones, PDA) in order to support elderly-monitoring. Another architecture but for the case of in-hospital patient-monitoring is presented by Chen et al in [91].

One common drawback of the presented health-monitoring solutions is their low flexibility and lack of the ability to be controlled and fine-tuned by the users (e.g. doctors, nurses or other medical professionals), where miniature devices (i.e. sensors) are configure only prior to deployment. Meantime, real-world requires high flexibility from health-monitoring FWNs, as their configuration has to account not only for the types of the patients (e.g. patients with Parkinson's disease, cardiac patients etc.) but also how their conditions evolve [92]. Also FWNs should account for possibilities that additional information may be required by medical personnel, or improvement of delivery quality for the existing data may be requested. However, only a limited research effort has been dedicated to developing of reconfigurable wireless solutions that will provide such a flexibility. Thus, [93][94] concentrate on designing reconfigurable miniatured devices themselves. Keoh et al [95] present an architecture that allows policy-driven control of sensors of an individual WBAN. Research work developed in [96][97][98][99] concentrate on how to reconfigure distributed applications and services operating over a wireless network. However, to the best of our knowledge no existing research explores the possibility of fine-tuning the actual delivery mechanisms utilized by the FWNs (i.e. ad-hoc routing, MAC protocols). This possibility is considered by the research of this thesis.

2.2 WiFi AP modeling

CSMA/CA modeling has received attention from the research community over the recent years. Bianchi [100] considers a wireless single-hop network that operates under saturated traffic conditions. Bianchi makes a collision decoupling assumption that a packet transmission experiences a collision with a probability that does not depend on the collision history of the packet. The assumption allows Bianchi to describe behavior of a generic wireless network node by a Markov chain probability model. The model estimates performance of the network in terms of aggregated network throughput, average delay gained at the MAC layer by a packet, and average packet retransmission number. The work has had a tremendous impact on CSMA/CA modeling approaches and resulted in a number of enhancements of the original model that have been presented later. Examples of these enhancements include models for non-saturated cases [101][102][103]. For example, Ergen and Varaya [104] present an enhancement that accounts for the possibility for network nodes to transmit at different rates. Zheng et al. [105] and Lu et al. [106] propose an enhancement that accounts for imperfections of the physical channel. A number of studies were also dedicated to the QoS-aware CSMA/CA version of the

IEEE 802.11e standard. Examples of these studies can be found in [107][108][109]. Modeling networks operating under non-saturated traffic conditions requires introducing additional so-called post back-off states. A node enters these states once it has completed its own transmission and has no further packets. These states were introduced in [110] and [111]. [112][113] present research dedicated to packet buffer modeling for wireless nodes. Markov models of the CSMA/CA mechanism have become extremely popular and present the majority of the research. However, an alternative approach can be found in [114], [115], [116] and [117]. The approach jointly uses $G/G/1$ queue and Probability Generating Function modeling techniques. Each node of a wireless network is modeled as a $G/G/1$ queue, while Probability Generating Function modeling is utilized to represent the wireless media.

Though CSMA/CA modeling has received certain attention, not all performance aspects have been studied sufficiently. Mostly all models target issues of throughput and fairness, while delay related issues remain obscure. Almost all presented above papers provide estimations for average transmission delay for a packet, while estimating delay distribution is not considered. Additionally, energy-related modeling of the CSMA/CA operation has received only marginal attention. In particular, since green ICT is going to be an issue in the near future, maintaining joint energy efficiency and quality of service is highly important. In this thesis we consider modeling of the CSMA/CA mechanism in order to estimate distributions for packet delay and transmission energy.

Chapter 3

Research Summary

This chapter summarizes the findings of the research presented in this thesis, where we present our conclusions (Section 3.1) and then provide some topics that could serve as a continuation of the research (Section 3.2).

3.1 Conclusions

Conclusions are presented as answers to the research questions that also are the objectives of this research. Our answers to the research questions are as follows.

- ***P1-RQ1. Multi-channel MAC cooperation:*** *How should node cooperation at the MAC layer be established in order to provide efficient multi-channel transmission?*

  Conclusion: Cooperation between miniature FWN nodes has a tremendous potential to provide efficient use of multiple channels by the network nodes. However, certain cooperative protocols are subject to appearance of the RCB problem. A good example of a protocol with the RCB problem is the CAM-MAC protocol that supports multi-channel data transmission scheduling based on the information collected by the neighbors. To counter the problem the protocol has been extended to support Virtual Topology Inferencing. The new protocol developed in this thesis is known as CAM-MAC-ARCB. Performance evaluation has shown that CAM-MAC-ARCB improves performance compared to CAM-MAC in terms of throughput and packet transmission delay.

- ***P1-RQ2. Adaptive routing:*** *How should nodes of a FWN cooperate at the Network layer in order to adapt to various load heterogeneities?*

  Conclusion: To support adaptive routing a FWN should incorporate a cross-layer node cooperation that stretches across Data Link (MAC sublayer) and IP layers. The research has developed a cross-layered MAC&Network layer protocol [26] for single transceiver device by integrating the CAM-MAC-ARCB and the PGBR Gradient Based Routing. The MAC layer node cooperation allows each node to establish its own capacity for packet forwarding. The IP layer cooperation between nodes forming a route allows understanding the forwarding capacity of the route. The performance of the protocol has shown improvement and robustness over the conventional routing protocols.

- ***P1-RQ3. Flexibility:*** *What are the side-effects of the proposed cooperation with regards to the FWN performance?*

  Conclusion: The proposed cross-layer protocol allows miniature FWN nodes to adapt to various load heterogeneities found within the network. The adaptation improves performance of the network in terms of load balancing and packet delivery ratio. However, the improvement comes at a price that involves an increase in node energy consumption, number of negotiations of the networks nodes and RCB rate.

- ***P1-RQ3. Flexibility:*** *In what way should the cooperation be managed in order to achieve a reasonable balance between the performance improvements and the side-effects?*

  Conclusion: The proposed cross-layer protocol exhibits flexibility to a sufficient degree in order to support a variety of service classes with respect to their ranking. Even though we have considered only the health monitoring scenario, the findings apply to any other application scenario that allows ranking the service classes in FWNs.

- ***P1-RQ4. User-control and fine-tuning:*** *What mechanisms should be integrated into the architecture of the FWNs to allow user-control and fine-tuning of the cooperation?*

  Conclusion: To allow user control and fine-tuning architecture, a miniature FWN node should incorporate a hierarchy of performance modification policies. The hierarchy should incorporate rules that configure the proposed protocol as well as rules that describe reduction of the network traffic of low priority class. The research has proposed a hierarchy of high-level policies for remote health-monitoring of a patient in a hospital environment. The policies allow medical officers to influence performance of the FWN network operating within the hospital. The policy hierarchy can configure the gradient routing parameter as well as reduce the network traffic of low priority class. Identification and resolution of conflicts between the policies requires pre-deployment analysis.

- ***P2-RQ1. CSMA/CA modeling:*** *How could the CSMA/CA mechanism be modeled in order to predict quality of service (delay guarantees) as well as energy efficiency of a WiFi AP?*

  Conclusion: Deep understanding of quality of service (delay guarantees) and energy efficiency provided by the CSMA/CA mechanism requires accurate modeling of the following network performance metrics: packet delay and transmission energy. A random sum model is presented by this thesis in order to support such modeling. The model allows to estimate numerical distributions for each of the two metrics as well as their joint distribution.

3.2 Future work

We consider that the following topics may serve as possible directions of continuation for the research presented in this thesis.

- ***Co-existence and cooperation of WiFi APs and miniature FWN devices:***
  The research presented in this thesis separately considers operation of WiFi APs and miniature devices of a FWN. However, FWN nodes of these two types may not only share the same 2.4GHz frequency bandwidth and IEEE 802.11 transmission technology, but may also be required to cooperate. For example, the in-hospital patient monitoring may be extended to operate in other location (e.g. kindergartens, schools, universities, and others), where monitoring results may be delivered to medical personnel located in the hospital via the Internet that is reached via cooperation between miniature devices and WiFi APs. Therefore, future research should also consider aspects

of co-existence and cooperation between devices of the two types.

- ***Broader range of communication patterns:***

  The research scope of the thesis focuses specifically on the uni-cast communication, while other communicational patterns such as any-cast, multi-cast, many-to-many are also rather common for the FWN applications. For example, a FWN may be formed by a number of miniature devices monitoring pollution/pollen levels within a certain location (e.g. hospital). Results of the monitoring may be forwarded to a remote competence center via a set of gateway nodes (any-cast communication), where certain analytics from the center may be delivered to the users through the FWN (multi-cast communication). Alternatively, miniature devices may forward monitoring results directly to the users via other nodes of the FWN (many miniature devices to many users, or many-to-many communication). Therefore, one possible direction for future research is to explore possibilities of extending the proposed cross-layer cooperation to support either any-cast, or multi-cast, or many-to-many communication.

- ***Delay Tolerant Networking:***

  Another future research direction is represented by the recent popularity growth of the Delay Tolerant Networks (DTN). Thus, some of the information contained by a FWN may be delay tolerant. For example, a FWN deployed at a certain location may loose its connectivity due to failure of some of its miniature devices. In this case the FWN may use social activity of the users and their mobility to exchange delay tolerant information between its disjoint segments. This will partially restore integrity of the services provided by the FWN till the failed devices are replaced and the original connectivity of the FWN is restored. Alternatively, the FWN may initially consist of a number of disjoint segments located at various rural or remote areas. In this case using social activity and mobility of the users is the only way for packet exchange between these segments.

- ***Social awareness:***

  Great size and/or variety of information dealt with by certain FWNs present another direction for future research. Thus, the delivery of such a diverse information should be accomplished in an efficient as well as user-aware fashion. Exposing each user to all of the available information may result in unnecessary resource expenditure and may also have an overwhelming effect on the user. Meanwhile, maintaining detailed user profile information is highly problematic in the case of FWNs due to the resource limitations of their nodes. Therefore, all necessary user information should be maintained by the network nodes collectively. However, user profiling, clustering, and other analysis may be of significant computational complexity that lays beyond the limited capacity of miniature FWN devices, and that is why this future research direction should incorporate necessity of integration of the FWN with an external server/cloud in order to outsource such a complex computing.

- ***Multi-hop CSMA/CA modeling***

  The proposed analytical model for the CSMA/CA mechanism is limited to the case of single-hop transmissions. Therefore, another possible direction for future research is to extend the model so it caters for a more generic case of multi-hop transmissions.

Chapter 4

Complete List of the Publications

This chapter presents the complete list of research articles of the author. All publications are presented in the reversed chronological order.

Published Articles:

P1. S. Ivanov, C. Foley, S. Balasubramaniam and D. Botvich, "Virtual Groups for Patient WBAN Monitoring in Medical Environments," IEEE Transactions on Biomedical Engineering, vol. 59, no. 11, pp. 3238 - 3246, 2012. **(AR<16%)**

P2. S. Ivanov, D. Botvich, and S. Balasubramaniam, "Cooperative Wireless Sensor Environments Supporting Body Area Networks," IEEE Transactions on Consumer Electronics, vol. 58, no. 2, pp. 284 - 292, 2012.

P3. S. Ivanov, D. Botvich, and S. Balasubramaniam, "On delay distribution in IEEE 802.11 wireless networks," in Proceedings of IEEE Symposium on Computers and Communications, pp. 254 - 256, (Corfu, Greece), 2011.

P4. S. Ivanov, D. Botvich, and S. Balasubramaniam, "Joint throughput and packet loss probability analysis of IEEE 802.11 networks," in Proceedings of IEEE Symposium on Computers and Communications, pp. 673 - 676, (Riccione, Italy), 2010.

P5. S. Ivanov, D. Botvich, and S. Balasubramaniam, "Gradient Based Routing support for Cooperative Multi-Channel MAC in Ad Hoc Wireless Networks," in Proceedings of International Conference on Advanced Information Networking and Applications, pp. 541 - 547, (Perth, Australia), 2010.

P6. S. Ivanov, D. Botvich, S. Balasubramaniam, and N. Popova, "Avoiding redundant channel blocking in cooperative multi-channel MAC protocols through virtual topology inferencing," in Proceedings of International Conference of Communications CoCoNet2 Workshop, pp. 1 - 5, (Dresden, Germany), 2009.

Submitted Articles:

P7. S. Ivanov, D. Botvich, and S. Balasubramaniam, "Joint delay and energy model for IEEE 802.11 networks", pp. 1-10, 2012

Bibliography

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[2] "IEEE Standard for Information Technology - Telecommunications and Information Exchange Between Systems - Local and Metropolitan Area Networks-Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," *IEEE Std. 802.11-1997*, 1997.

[3] "Supplement to IEEE Standard for Information Technology - Telecommunications and Information Exchange Between Systems - Local and Metropolitan Area Networks - Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: High-Speed Physical Layer in the 5 GHz Band," *IEEE Std. 802.11a-1999*, 1999.

[4] "Supplement to IEEE Standard for Information Technology - Telecommunications and Information Exchange Between Systems - Local and Metropolitan Area Networks - Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Higher-Speed Physical Layer Extension in the 2.4 GHz Band," *IEEE Std. 802.11b-1999*, 1999.

[5] "IEEE Standard for Information Technology - Telecommunications and Information Exchange Between Systems - Local and Metropolitan Area Networks - Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," *IEEE Std. 802.11g-2003*, 2003.

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Appendix A:

"Avoiding Redundant Channel Blocking in Cooperative Multi-Channel MAC Protocols Through Virtual Topology Inferencing"

Avoiding redundant channel blocking in cooperative multi-channel MAC protocols through virtual topology inferencing

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***Abstract*—Large scale distributed ad hoc networks require cooperative mechanisms of channel allocation in order to increase efficiency of the network. The mechanism of channel allocation, which is used in the Medium Access Control (MAC) sub-layer for wireless devices in IEEE 802.11 standard, allows communication through a single MAC channel. However, as a number of nodes increases, the throughput is reduced through the use of single channel. Nevertheless, using multiple channels solves this problem and allows achieving higher network efficiency. Cooperation techniques of channel allocation have been investigated by T. Luo et al [6] as an asynchronous cooperative multi-channel MAC protocol (CAM-MAC), which uses cooperative neighbour updating and vetoing concept for channel selection. The technique allows nodes to efficiently select channels which in turn allows higher network performance. However, using such cooperative technique can lead to "Redundant channel blocking", which blocks certain nodes to use valid channels that are not in range with nodes using the same channel. In this paper, we propose a solution to mitigate this problem using virtual topology inferencing, where simulations have also been presented to validate the proposed solution.**

I. Introduction

The IEEE 802.11 standard supports wireless data transmissions [9], where it uses single data channel for MAC layer and supports multiple channels in physical layer. Due to the single channel in the MAC layer, each node has to share this channel with all other nodes located in its transmission range and effectively use the same channel for control as well as data transmission. When the number of nodes increases, this leads to noticeable performance degradation. One solution to this problem is to increase the number of channels in order to increase the overall throughput. However, this technique poses certain challenges for large scale distributed ad hoc networks. One of these challenges stems from the limitations of IEEE 802.11 device, where each device is equipped with only a single half-duplex transceiver. Therefore, each device is only allowed to transmit or listen to only one channel at a time. In the event the device is transmitting data through a channel or listening to a channel, it doesn't have the ability to listen to communications through other channels.

One approach towards supporting distributed channel allocation for single transceiver devices is through cooperation. However, most solutions have limitations such as tight clock synchronization or require modifications to standard IEEE 802.11, which make their implementation quite difficult. However, the CAM-MAC solution given in [6] does not require time synchronization or changes to standard equipment. However, one drawback of the solution is when information of selected channels are propagated to distant nodes, which can prevent nodes from using the specific channel even if the node's using that channel is not in range. We refer to this phenomenon as "Redundant channel blocking" (RCB) problem. In this paper we investigate the RCB problem, and propose a solution towards mitigating this problem through virtual topology inferencing knowledge. Nodes will observe negotiations performed by other nodes and determine the topology of neighbouring nodes. Based on the virtual topology, nodes will be able to accurately cooperate with other nodes during the channel allocation process.

The rest of the paper is organized as follows: Section II presents the Related Works. Section III describes the cooperative negotiation of existing work, while section IV describes RCB problem. Section V presents the virtual topology inferencing technique, and Section VI presents the simulation of the proposed approach. Finally section VII presents the conclusion.

II. Related work

In this section, Split phase [8] solutions for multi-channel MAC protocols are presented. As mentioned before, all the solutions use standard IEEE 802.11 equipment which contains a single half duplex tuneable transceiver [9]. Each device contains a "control channel", and the remaining channels that are used for data transmission are known as "data channels". The control channel is used for negotiating the data channels with the neighbouring nodes.

The MMAC protocol, proposed by So and Vaidya [1] allows transmitting data through both control channel and data channels. The control channel is predefined for all nodes and is divided into Beacon intervals of fixed size where each interval contains an ATIM window, and the remaining interval is for data transmission. In each ATM window, nodes negotiate in order to schedule data transmissions. All nodes are tuned to the control channel in each ATIM window which requires time synchronization between the nodes. At the same time, fixed size Beacon interval results in time wastage in cases of different packet sizes. Maheshwari et al. [2] proposed a similar protocol with variable ATIM window size. Cordiero and Challapali [3] proposed the C-MAC protocol where nodes negotiate in predefined slots as it is done in MMAC. The distinguishing feature of C-MAC is using dynamically defined and distributed control channel. A disadvantage of this protocol is that the negotiation duration must include all neighbouring nodes. This leads to a restriction on the amount of neighbours, which can be large in real deployment situations. Extending the negotiation phase will make the protocols inefficient for topologies with small node density.

The AMCP protocol, proposed by Shi et al [4] allows nodes to negotiate through the control channel to select a suitable data channel for transmissions. During negotiation, each node can get information of utilized channels and avoid using these channels. However, during data transmission the sender and the receiver don't listen to the control channel (since they have switched to the data channel). Hence they are not fully aware of new channels that are selected by the neighbours, and in the events the node selects the same channel this will lead to data collision. To solve this problem the sender and the receiver refrain from using those channels for duration of one data packet transmission. This leads to increasing of packet transmission delay and data channels underutilization. A similar problem is also encountered in the Bi-McMac protocol, proposed by Kuang and Williamson [5]. However, the CAM-MAC protocol proposed by T. Luo [6], counters the problem above by allowing the neighbours to further propagate information to other neighbours during negotiation, to update the latest channels being used by surrounding nodes. The next section will describe the CAM-MAC [6] protocol. Results from [6] show that CAM-MAC protocol is more efficient than IEEE 802.11. However, CAM-MAC has certain drawbacks, which affect performance. In this paper we show the appearance of one of them, and present a solution towards mitigating this problem.

III. Cooperative negotiation

Our solution is based on the extension of the CAM-MAC protocol. In the solution we only consider cases with available routing mechanisms between nodes. The bandwidth is divided into multiple orthogonal channels, and each node has a single IEEE 802.11 transceiver. The transceiver can transmit or listen to only one channel at a time. A node is able to receive data from a neighbour which is within a certain transmission range of the node only if there is just one neighbour transmitting in the range through the channel the node is tuned to.

Similar to the AMCP and the Bi-McMac protocol, the CAM-MAC negotiates through a fixed control channel, and transmits data through the data channel. However, the CAM-MAC protocol has a technique of updating its neighbours of the current channels being used by the surrounding nodes. The next section will briefly describe the CAM-MAC negotiation process. For the process of negotiation we use the terms "control session", while we use the term "data session" during the process of data transmission. During a data session, a sender transmits only one fixed size data packet. To ensure reliability of packet delivery, an acknowledgment is sent back through the selected data channel to confirm the receipt of the data packet.

A. Negotiation without cooperation

In this section we illustrate a negotiation process with an example which helps to understand the benefits given by the current techniques. Each time a node is neither receiving nor sending data, the node will change to the control channel (in the idle state) and collect information about states of data channels by listening to the neighbour's negotiation. However, the nodes can't collect that information when they're taking part in data transmission because they are equipped with only one half-duplex transceiver. Therefore, during transmission nodes will not be aware of the latest channels used by neighbouring nodes. This problem only arises when the nodes do not have full knowledge of the channels currently used by its neighbours and have no cooperative mechanism. Fig. 1 (a) - (c) illustrate a case when the nodes negotiate with out full knowledge.

In the example presented in Fig. 1 (a), initially a data transmission from Node 1 to Node 2 through Channel 1 was established. During the negotiation between nodes 1 and 2, the surrounding nodes were updated that channel 1 is used.

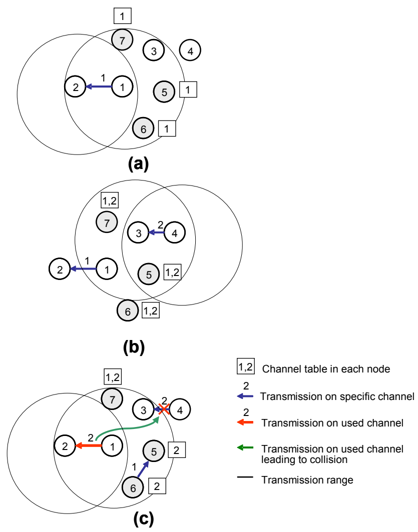


Fig. 1. Drawback of a negotiation with limited information

Immediately after that node 3 and 4 began negotiating using channel 2, and again this information is updated to surrounding nodes (Fig. 1 (b)). However, this occurred when nodes 1 and 2 were transmitting through Channel 1. Therefore, nodes 1 and 2 will not have new updated information about channel 2 being used by nodes 3 and 4. Now let's consider Nodes 5 and 6, which began negotiating and transmitting through Channel 1 after nodes 1 and 2 finished. In the event that nodes 1 and 2 would now like to use 2 they will successfully negotiate and begin using the channel. This is due to the fact that the negotiation between Nodes 3 and 4 occurred when Nodes 1 and 2 were transmitting data, and, nodes 1 and 2 will not have knowledge that channel 2 is used. Therefore, if Node 1 begins sending data through Channel 2, it will destroy the data transmission of Nodes 3 and 4.

B. Negotiation through CAM-MAC

In order to mitigate the problems of channel collision, the CAM-MAC [6] protocol incorporates vetoing technique through cooperation of neighbouring nodes. In the event that Node 1 and 2 would like to transmit through channel 2, a request will be transmitted from Node 1 to 2. This request will be heard by node 7, which will then veto the request, leading Node 1 and 2 to back-off and renegotiate after the first data channel release. Therefore, the benefits of the CAM-MAC protocol is to update nodes with the latest knowledge of used channels in order to minimize any possible collision with nearby nodes that are using the channels.

IV. Redundant channel blocking

Although the CAM-MAC protocol ensures the nodes are fully updated with the latest information, there is a major drawback with the protocol.

This drawback is an appearance of RCB problem which is illustrated in Fig. 2 (Fig. 2 is the example from Fig.1). As described earlier, the information of channel 2 being used by Nodes 3 and 4 is propagated to Node 5 and 7, which are in the ranges of Nodes 3 and 4. The drawback with this is that, in the event that Node 6 would like to transmit data and begin negotiation, Node 6 will not be able to use channel 2 even though it is out of range from nodes 3 and 4. This will occur because when node 6 begins negotiation, node 5 will immediately veto and prevent node 6 from using channel 2 even if nodes 6 and 2 are out of range from nodes 3 and 4. This will in turn prevent nodes from transmitting at higher throughput, if the knowledge used channels in the neighbourhood is not clearly propagated.

To address RCB problem a node should not only determine the channels that are used in the neighbourhood, but also determine the surrounding topology. The mechanism of topology estimation is described in the next section.

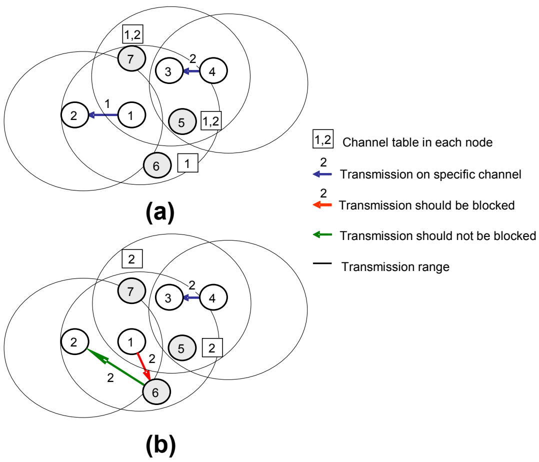
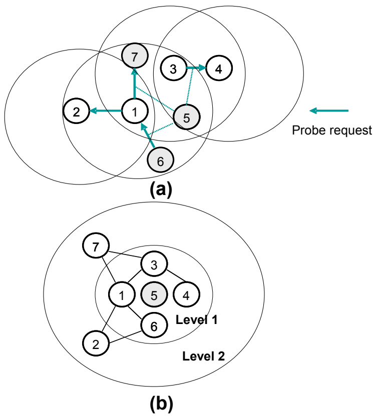


Fig. 2. Redundant channel blocking

V. Virtual topology inferencing

As we mentioned above using just information of data channel states leads to appearance of RCB problem. In the example shown on Fig. 2(b) if Node 5 knew that Nodes 6 and 2 don't share the same media it would not block Node 6 of using Channel 2. In order to avoid such a problem, we propose a virtual topology inferencing technique that each node performs by listening to neighbours negotiations. Fig. 3 illustrates the mechanism of virtual topology formation.

Fig. 3(a) illustrates the mechanism, where node 3 will listen to the neighbours' negotiation process. During the negotiation process, each node transmits in its control session a probe request which contains the source and destination address, and



Level 1	Level 2
3 (1, 4)	7
4 (3)	
6 (1)	2
1 (3, 6)	2, 7
⋮	⋮

(c)

Source	Destination	Channel
3	4	1
1	2	2
⋮	⋮	⋮

(d)

Fig. 3. (a) Node 5 sensing neighbours probe request, (b) virtual topology, (c) virtual topology table by node 5, and (d) channel table of node 5

and the channel being requested. Node 5 will then categorise the different source and destination addresses and their corresponding nodes to either level 1 or level 2 neighbours in its virtual topology. Level 1 indicates that the node is an immediate neighbour, while level 2 indicates the node is a neighbour of the neighbouring node (Fig. 3 (b)). This will therefore lead to each node containing two tables, which is the table of virtual topology (Fig. 3 (c)), and the table of channels used by the neighbouring nodes (Fig. 3 (d)).

Fig 4 illustrates based on the scenario of Fig. 2 (b) the negotiation process for both cooperation with and without virtual topology knowledge. The negotiation process is with respect to node 5's vetoing activity with neighbouring nodes. As shown in Fig. 2, in the event that node 4 and 3 start transmitting on channel 2, this information will be recorded by node 5.

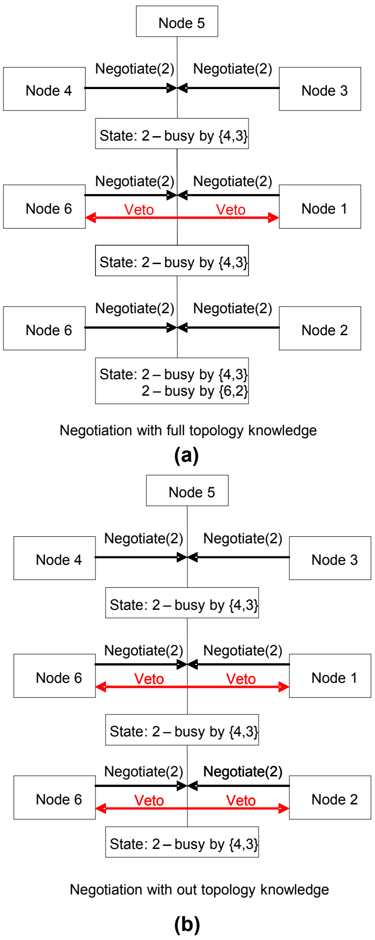


Fig. 4. (a) Cooperative negotiation with virtual topology knowledge, (b) cooperation without virtual topology knowledge

Fig. 4 (b), shows that when both node 6 and 1 or node 6 and 2 negotiate to use channel 2, this will be blocked by node 5. However, in the case of cooperation with virtual topology knowledge in Fig. 4 (b), only the node 6 and 1 will be blocked by node 5 from using channel 2. Our technique allows nodes continually inference and learn of new nodes in their neighbourhood which is an advantage supporting networks with node mobility.

VI. Simulation

In order to validate our virtual topology inferencing and its benefits, we have performed simulations and compared to the CAM-MAC protocol [6] (Our solution avoiding RCB problem is referred to as CAM-MAC ARCB). Our simulation is divided into two sections, which includes tests for 40 nodes with different loads, and for different number of nodes with 60% load.

A. 40 node topology with varying load

Fig. 5 - 7 presents the results of our simulations. We use pair-wise networks where nodes form sets of pairs and each node sends (receives) data to (from) another node of its pair. Nodes form grid topology. We assume that upper layer functionalities (e.g. routing) have been set and rely on the underlying MAC layer to allocate the channel for transmission. In each simulation, nodes generate heterogeneous traffic attempting to use a certain percent of

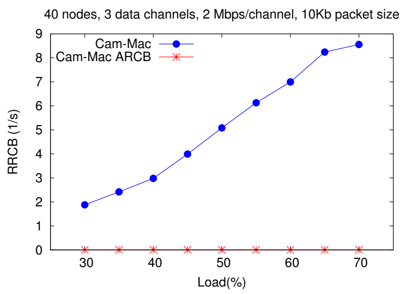


Fig. 5. Rate of channel blocking

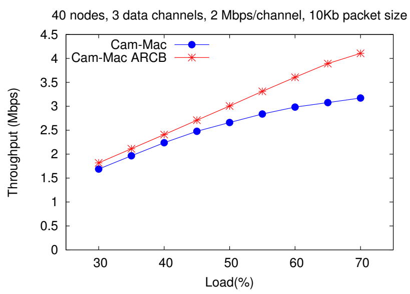


Fig. 6. Average throughput

available data channels which we call “Load” (%). Data packets are generated at each sender according to a Poisson process. Each node is equipped with a transceiver which allows it to work with one control channel and 3 data channels of 2 Mbps channel capacity each. All statistics are averaged over results of 10 different simulations with the same parameters. Each simulation is performed on a static ad-hoc network of 40 nodes with average neighbouring node density of 15. In the simulations, we consider each MAC layer packet delivery timeout to be 100 ms which indicates maximum stay of a packet in a queue. To evaluate the performance comparison with CAM-MAC, we use the following metrics: Average throughput - average amount of data which delivery was successful through a negotiated channel; Average Delay overhead - an average time that a successfully delivered packet has spent in the buffer while waiting for a free channel (ms); Rate of RCB cases (RRCB) - an average number of times when negotiation of eligible channel was vetoed (1/s).

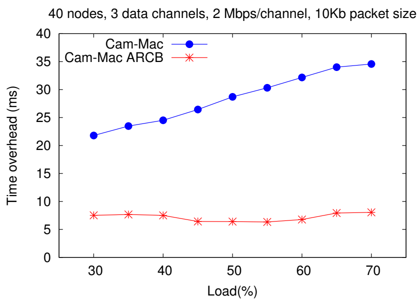


Fig. 7. Delay Overhead

Fig. 5 illustrates the results for RRCB metrics and shows that the RCB worsens for CAM-MAC when the network load increases compared to CAM-MAC ARCB. Fig. 6 illustrates the average throughput and shows that as the network load increases, the virtual topology benefit increases (there is a very little difference when the load is low, but CAM-MAC ARCB is still slightly better than CAM-MAC). Fig. 7 illustrates the delay overhead that packets waited in the buffer before transmission, and as shown in the result, the delay is reasonably static for all loads in CAM-MAC ARCB case, but worsens for CAM-MAC as the network load increases.

B. Varying number of node with 60% load

The results for varying number of nodes with 60% load are illustrated in Table 1 and 2. The results illustrate that as the topology size increases, the average throughput, average delay overhead, and RRCB for CAM-MAC ARCB outperforms the CAM-MAC. At the same time, we can see more stable results for CAM-MAC ARCB as the number of nodes increases for all metrics.

TABLE I
PERFORMANCE FOR CAM-MAC

No. of nodes	Average Throughput (Mbps)	Average Delay overhead (ms)	RRCB
50	2.93	31.84	6.59
60	2.79	31.48	6.87
70	2.75	32.05	6.87

TABLE II
PERFORMANCE FOR CAM-MAC-ARCB

No. of nodes	Average Throughput (Mbps)	Average Delay overhead (ms)	RRCB
50	3.59	7.50	0.003
60	3.61	7.09	0.003
70	3.59	8.57	0.0031

VII. CONCLUSION

The use of multiple channels on single transceiver devices ensures higher throughput capability for wireless networks with large number of nodes. However, a distributed channel allocation mechanism is required to support large number of nodes. Cooperation between the nodes can help ensure that channels are efficiently allocated between the nodes. In this paper, we have identified RCB problem for one negotiation protocol known as CAM-MAC and extended this through virtual topology inferencing to improve its performance. Simulation comparison has also shown the improvements for varying network loads.

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Appendix B:

"Gradient Based Routing support for Cooperative Multi-Channel MAC in Ad Hoc Networks"

Gradient Based Routing support for Cooperative Multi-Channel MAC in Ad Hoc Wireless Networks

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***Abstract*—Growing popularity of wireless ad hoc networks leads to higher demands on performance of all TCP/IP stack layers. Usually ad hoc networks operate according to IEEE 802.11 standard which provides a MAC layer protocol that uses a single channel for data transmissions. However, increasing the number of data channels on MAC layer improves performance of ad hoc wireless networks by letting nodes simultaneously transmit data through different channels. Nevertheless network performance improvement will be diminished if routing mechanisms are not efficient and reactive to load changes within the network. In this paper we introduce a multi-channel MAC layer cooperative technique that integrates gradient based routing to support multi-hop wireless transmission. We show that using the gradient based routing to support multi-channel MAC protocols can enhance overall throughput of the network, and improve network load balancing. Simulations have also been conducted to validate the proposed solution.**

***Index Terms*—Multi channel MAC cooperation, Gradient based routing.**

I. INTRODUCTION

Research into wireless ad hoc networks has received increase attention in recent years. Users can use such networks not only to access the Internet, but also to stream data between the ad hoc nodes (e.g. file transfer or multimedia streaming). In recent years, we have seen increase in the number of services that could benefit greatly and suit ad hoc network environments. A good example is the increase in popularity of social networks, which could make use of ad hoc networks to support interaction between members who belong to the same community and have similar interests. Another example is a cost effective mechanism of disseminating information to mobile nodes in a specific locations (e.g. advertisements in shopping centres to users within the vicinity). Due to these factors, various researches have been conducted to support ad hoc networks (e.g. cognitive radio [12], cooperative MAC, cross layer design). In particular, special attention has focused on cooperative multi-channel MAC protocols [9], [11].

Typically wireless networks operate according to IEEE 802.11 standard [1], which allows the usage of a single data channel in the MAC layer, while on physical layer, the standard allows using a number of different channels. Thus, nodes of the same range share the same data channel and use it for transmitting both control information and data. One of the proposed solutions that extended from this is to create a number of data channel in the MAC layer for data transmissions. This will allow different nodes to transmit data in parallel, which in turn will increase performance of the overall wireless network. A number of ways for implementing this technique have been investigated and cooperation in the MAC layer is one of them. Some cooperative solutions have different limitations, such as requirement of clock synchronization or extra modifications at the physical layer. Luo et al ([3], [9], [10]) presented a cooperative technique called CAM-MAC, which is an asynchronous cooperative MAC solution. Through negotiations, the nodes can make parallel transmission, which in turn increases the performance. Further studies presented in [11] show that extending CAM-MAC negotiations to infer locations of nodes within the vicinity can prevent redundant channel blocking, which further increases the overall throughput performance.

As mentioned above, using a multi-channel MAC protocols for data transmissions can improve overall throughput by increasing simultaneity of transmissions between the nodes. However, the network performance improvement will be diminished, if appropriate routing mechanisms are not integrated to support the multi-channel MAC when performing multi-hop transmissions. In this paper, we present a solution that integrates an adaptive gradient based routing to support cooperative multi-channel MAC devices. Simulation tests have shown that our solution improves the simultaneous transmission of data and also improves the overall network performance when compared with standard routing technique (e.g. AODV).

The rest of the paper is organized as follows: Section II gives an observation of existing MAC layer cooperation techniques; Section III gives a general overview the proposed solution; Section IV presents DISH cooperation technique; Section V explains proposed local load estimation technique in conjunction with extension of AODV routing technique. Section VI presents results of simulations which have been conducted; and Section VII presents conclusions.

II. RELATED WORK

In [2], Mo et al presented an overview of existing multi-channel MAC protocols. Cooperative MAC protocols of that type are referred as “Split phase” protocols. “Split phase” MAC protocols use only one channel for exchanging control information (this is referred to as “control channel”), and the remaining channels for data transmission. The nodes are

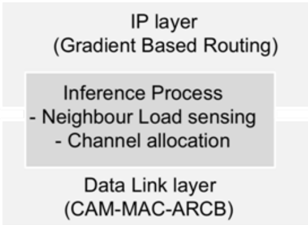


Fig. 1. Proposed solution for Integrated Gradient Based routing and Cooperative M-MAC

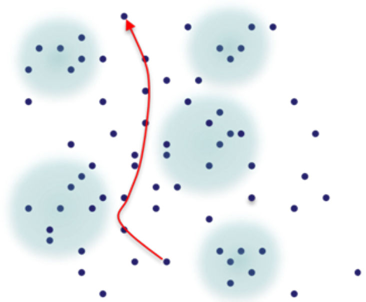


Fig. 2. Illustration of routing round regions of high load in ad hoc networks

usually tuned into the control channel and use this channel for negotiating the use of data channels. Through the control channel, the nodes can listen to negotiations made by neighbouring nodes. The control channel may be used for negotiations exclusively, like it's done in CAM-MAC protocol [3], or for data packet transmissions as it's done in MMAC protocol proposed by So and Viadya [4]. In the MMAC protocol, cooperation is performed by simple scheduling of data packet transmissions, where the scheduling process is performed by the nodes in predefined intervals of fixed length. However, the length of scheduling intervals may also be variable (Maheshwari et al [5]). Cordiero and Challapali [6] defined a mechanism to allow nodes to dynamically use control channels for scheduling data transmissions. The main disadvantage of such scheduling protocols is that the negotiation must include all neighbouring nodes. While having a control channel to listen to neighbour negotiations is ideal, the devices would require two transceivers. Another solution is to have a single transceiver, where nodes can switch from control to data channel, interchangeably (e.g. Shi et al. [7]). Once the sender and the receiver have agreed on a data channel, both nodes will switch to that channel and begin data transmission. During this operation, the neighbouring nodes will record the occupied data channel and use this information to avoid any possible collisions. However, when the sender and the receiver are tuned to the data channel, they miss out on hearing new negotiations made by their neighbours. Therefore, nodes will not be aware of new data channels that are established. To avoid possible collisions and gain new knowledge of used data channels during channel switching, the sender and the receiver hold off any attempt for data transmission once they have completed their own data transmission (this is to give the sender and receiver a certain amount of time to learn of new used data channels). However, this will leads to increase in packet transmission delays, which was encountered in Bi-McMac protocol, proposed by Kuang and Williamson [8]. A solution to mitigate this problem is proposed by Luo et al [3], [9], [10] (DISH cooperation technique), where neighbours are allowed to update other neighbours of latest data channels used and veto any invalid negotiations made by the neighbours.

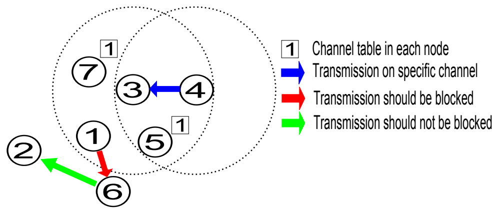


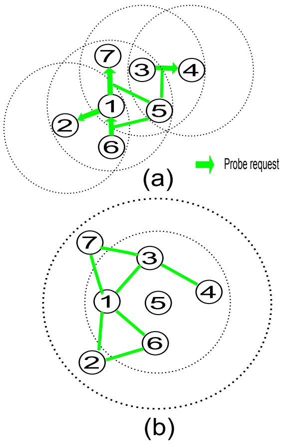
Fig. 3. Redundant channel blocking in CAM-MAC protocol

III. Integreated Solution

Our aim is to develop a solution for multi-hop routing support for communication devices that have multi-channel MAC protocols. Fig. 1 presents our proposed solution. The CAM-MAC-ARCB protocol is based on our previous work presented in [11] which extends the CAM-MAC protocol. While the previous solution only focused on single hop transmission, in this paper we extend this solution to support multi-hop transmission by using gradient based routing. Our solution targets specifically single transceiver devices with multi-channel MAC protocols. Since the future will witness increase usage of wireless ad hoc devices, our proposed solution targets environment with dense ad hoc networks that can support diverse services (e.g. data or multimedia). Such environments may lead to varying loads within the environments. In such cases, routing through lightly loaded regions of the network is ideal to maximize throughput within the network (this is illustrated in Fig. 2). The details of our proposed solution will be described in the following sections, where we will first describe the CAM-MAC-ARCB solution, followed by the gradient based routing.

IV. CAM-MAC-ARCB

In this section we provide a short description of the CAM-MAC-ARCB solution, while a full description can be found in [11]. As described in the related work section, the advantage of the CAM-MAC protocol is the ability of the neighbors to assist in the negotiation process, and help veto request of invalid



Level 1	Level 2
3(1,4)	7
4(3)	
...	...

(c)

Source	Destination	Duration
3	4	1
...	...	...

(d)

Fig. 4. (a) Node 5 sensing neighbours probe request, (b) virtual topology, (c) virtual topology table by node 5, and (d) channel table of node 5

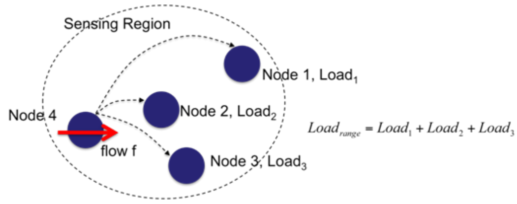


Fig. 5. Illustration of load sensing

channels made by neighboring nodes. A key problem with the original CAM-MAC protocol is that propagating information of selected channels to distant nodes can prevent nodes from using specific channels even if the nodes using those channels are not in range. We refer to this phenomenon as "Redundant channel blocking" problem. In order to avoid this problem, we developed the CAM-MAC-ARCB solution, which avoids unnecessary blocking of valid channels. Fig. 3 illustrates an example of this problem.

For example, in Fig. 3, for simplicity, nodes operate in the environment which allows using just a single data channel. Then, as in the figure the information of the channel being used by Nodes 3 and 4 is propagated to Node 5 and 7, which are in the ranges of Nodes 3 and 4. The drawback with this is that, in the event that Node 6 would like to transmit data and begin negotiation, Node 6 will not be able to use the channel even though both Node 6 and its receiver are out of ranges of nodes 3 and 4. Thus, both transactions from Node 1 to Node 6 and from Node 6 to Node 2 would be blocked. Appearance of this problem prevents nodes from transmitting at higher throughput, if the knowledge of used channels in the neighbourhood is not clearly propagated. In order to counter this problem, we incorporated topology inferencing, where each node is able to sense used channels and their respective range based on a virtual topology [11].

Fig. 4(a) illustrates the mechanism, where node 3 will listen to the neighbours' negotiation process. During the negotiation process, each node transmits in its control session a probe request, which contains the source and destination address, and the requesting channel. Node 5 will then categorise the different source and destination addresses and their corresponding nodes to either level 1 or level 2 neighbours in its virtual topology. Level 1 indicates that the node is an immediate neighbour, while level 2 indicates the node is a neighbour of a neighbouring node (Fig. 4(b)). This will therefore lead to each node containing two tables, which is the table of virtual topology (Fig. 4(c)), and the table of channels used by the neighbouring nodes (Fig. 4(d)).

Coming back to our example in Fig. 3, while node 5 records the information of nodes 3 and 4 transmitting on channel 2, node 6 and 1 will be the only nodes to be blocked by node 5 from using channel 1. This is turn will allow nodes to increase their transmission capabilities compared to the CAM-MAC protocol.

V. Gradient Based Routing and Cooperative MAC Load Estimation

While the previous section presented the CAM-MAC-ARCB cooperative technique for improved channel allocation, this section will concentrate on route discovery. As described earlier, our aim is to determine a route (based on gradient based routing) that senses regions of lowest load. Implicitly, the solution will support more efficient scheduling at the MAC layer, since the load will be diverted to less congested regions of the network, which will improve the overall performance.

The approach for determining the gradient is based on load sensing within close vicinity of each node. The load sensing is performed periodically, where each node will then calculate the gradient value to the next hop using the load information. We will first present the cooperative load sensing operation for determining the load of nodes in close vicinity and then present the gradient based function.

A. Impact of load fluctuations

For each node of the neighbourhood, we call a part of shared resources that the node uses as load. This gives us an upper bound for a node load. For any node using n data channel for transmission its maximum load can't exceed $1/n$, as each node is equiped only with a single half-duplex transceiver and due to this reason can not use more then one data channel at a time. Thus for each node i:

$$0 \leq Load_i \leq 1/n = Load_{max} \tag{1}$$

$Load_{max}$ may be adjusted as well with respect to channel botleneck problem, which is considered in [3]. Load of the range would be formed as sum of loads of all nodes with in the range. Thus:

$$Load_{Range} = \sum_i Load_i \tag{2}$$

$$0 \leq Load_{Range} \leq 1 \tag{3}$$

Let's consider an example of load sensing presented in Fig. 5. Node 1, 2, 3 and 4 are within the sensing range of Node 4, where nodes 1 to 3 have a certain load ($Load_1$, $Load_2$ and $Load_3$, respectively). If in this situation a new data flow f is to be routed through a node i, it will lead to increase of load on the node and contribute to an increase in the range as well. Hence, if the data flow f contributes an additional load $Load_f$, then:

$$Load_i^{new} = Load_i + Load_f \tag{4}$$

$$Load_{Range}^{new} = \sum_j Load_j^{new} = \sum_j Load_j + Load_f \tag{5}$$

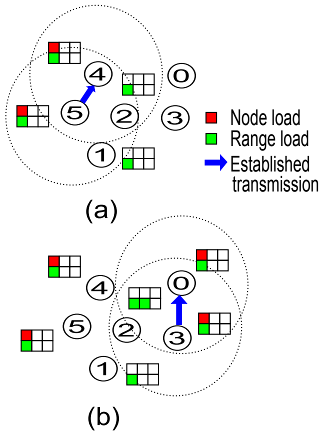
Combining equations (1) - (5) will lead to a new bound for the additional load, which can be brought to the range through the node i:

$$\begin{array}{lcl} 0 & \leq & Load_f \\ Load_f & \leq & Ability_i \end{array} \tag{6}$$

and $Ability_i = min\,(1 - Load_{Range}; Load_{max} - Load_i)$ describes the ability of node i to route new flows, for brevity we reference to this as "node ability" in the rest of the document. In the following section, an asynchronous autonomous cooperation technique for estimating values of node abilities will be presented.

B. Cooperative load sensing

In Section IV, we presented the CAM-MAC ARCB negotiation process for determining the most appropriate channel to select for data transmission. However, we extend the CAM-MAC-ARCB information passed during negotiation to incorporate load sensing. Therefore, the negotiation process includes not only the sender's and receiver's address and channel being requested, but also the duration of proposed transmission. Using this information, the estimation of spare node load and spare range load can be established in an autonomous and distributed manner. In our solution work, the estimation of load is performed in intervals (also known as load sensing interval). For each packet transmission going through a sensing range we define the load as the time share used by the transmission during the load sensing interval divided by the number of available data channels. We propose each node to be equipped with a load table, which is presented on Fig. 6(c), where initially all four values of the table should be set to 0. The values of the tables are updated at the end of the load sensing interval. Each time a node has been involved in a successful negotiation, the node updates the Range Load Collected (RLC) of the new load contribution (based on concept presented in section V-A). The RLC is used to sense the neighbouring loads. Each time a node has been involved in a successful negotiation as a sender or a receiver the node updates the Node Load Collected (NLC).



Load type	Collected	Estimated
Range Load	RLC	RLE
Node Load	NLC	NLE

(c)

Fig. 6. Cooperative MAC layer technique for load estimation

The process of load estimating is pictured on Fig 6(a)-(b). The NLC and RLC cells are represented as red and green bars above the node. There are two data flows: from node 5 to node 1 and from node 3 node 0. Initially, (Fig. 6(a)) node 5 successfully establishes a transmission to node 4, and would like to transmit 1 packet. For simplicity, we will say that nodes operate in an environment which allows using 1 data channel at a time; and a transmission interval allows maximum 3 packets (therefore 1 packet transmission is equivalent to 1/3 load addition). According to the negotiation process nodes 1 and 2 (neighbours of nodes 5 and 4) supported the negotiation process. Therefore, the updates of the RLC and NLC cells are as follows: Nodes 1, 2, 5 and 4 add 1/3 to their RLC cells and nodes 5 and 4 add 1/3 to their NLC cells. After nodes 5 and 4 have finished their transmission, node 3 establishes a transmission to node 0, where the negotiation process involved node 2 as a neighbour of node 3 (Fig. 6(b)). The transmission between nodes 3 and 0 is also only for 1 packet. Therefore, nodes 0, 2 and 3 add 1/3 to their RLC cells; and nodes 0 and 3 add 1/3 to their NLC cells. As shown in Fig. 6(b), the range load within the sensing region of node 2 starts to increase after the two transmissions. This indicates the load of that region is increased due to increase activities of nodes within the region (e.g. transmission between nodes 5 to 4 and nodes 3 to 0).

The load table in Fig. 6(c) also includes the Range Load Estimation (RLE) and the Node Load Estimation (NLE), which are predicted values of the future range load and node

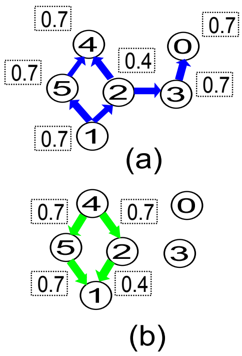


Fig. 7. Routing and load estimation

load. The prediction mechanism uses the exponential averaging of collected values for range and node load respectively. Once the sensing interval is completed, the node performs an exponential averaging of values for range and node loads, and the result of the averaging is updated in the RLE and NLE.

Once the node has completed the prediction process, it determines its own routing ability, which is calculated according to equation (6). Fig. 7 (a) shows node ability values for the scenario of Fig. 6. In this example the exponential smooth factor (β) is set to 0.1. Once node 2 has collected the load information, it has initial values for NLC, NLE and RLE, where the value of NLC cell is 2/3. Therefore, the exponential averaging would be:

$$\begin{aligned} Load_2 &= (1-\beta)\cdot NLC + \beta \cdot NLE \\ Load_2 &= 0.9 \cdot 0 + 0.1 \cdot 0 = 0 \\ Load_{Range} &= (1-\beta)\cdot RLC + \beta \cdot RLE \\ Load_{Range} &= 0.9 \cdot 0.667 + 0.1 \cdot 0 = 0.6 \end{aligned}$$

Nodes in the example use a single data channel for data transmission, thus according to equation (1) $Load_{max} = 1/1 = 1$, then $Ability_2 = min\,(1-0.6; 1-0) = 0.4$.

C. Gradient based routing

The previous section presented the mechanisms sensing the loads of the regions and determining the node abilities. The routing process is based on determining a path that traverses through nodes with maximum node abilities. The routing process is modifed from the AODV protocol, where the path will automatically change as the node abilities change, while AODV protocol considers only hop counts. Therefore, using the node ability values, the route discovery follows a gradient path to the destination. The gradient function is adopted and modified from our previous solution in [13], and is represented as,

$$G_{n,d,n\to j} = (1-\gamma)\cdot \Phi_j + \gamma \cdot h_{j,d} \tag{7}$$

where the Φ represents normalized ability of the route going through node j to destination d, and $h_{j,d}$ represents the normalised hop count of the route to destination d. In our solution, we assume that the hop count information is available

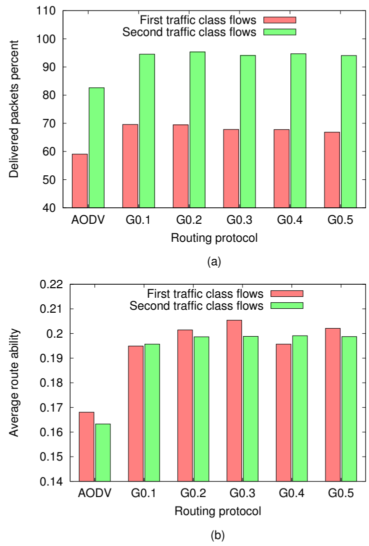


Fig. 8. Simulation results: (a) Percentage of delivered packets, (b) Average node ability along path

and normalized (e.g. nodes closer to the destination will have a value closer to 1; and less loaded nodes will have values closer to 1). An example of proposed routing technique is given in Fig. 7. Once node 1 wants to send data to node 4 it initiates route establishing process which is pictured on Fig. 7(a). The process of nodes replying to the route estimation process and establishing of the route abilities for different paths is pictured on the Fig. 7(b). Thus node 1 gets two routes where one of them goes through node 5 and another goes through node 2. Both routes have the same hop count value, but ability value for route going through node 5 is higher. Therefore, node 5 is selected since it has a higher gradient value. By picking node 5 as the next hop, data flow 1-4 goes through the route where it competes only against the flow going from node 5 to node 4, but if node 2 was chosen as the next hop, data flow 1-4 would have to compete against both data flows 5-4 and 3-0 since both nodes 3 and 5 are with in the transmission range of node 2.

VI. Simulation

We have conducted a simulation to validate our proposed solution. The main aim of the simulation is to determine the effectiveness of the Gradient based routing integrated with the CAM-MAC-ARCB negotiation protocol. The simulation compared network performance of AODV protocol and Gradient routing protocols using different weightings of γ. The simulations presented on Fig. 8 are conducted for wireless networks of 96 nodes, with an average nodes' density of 9. In each simulation nodes generate heterogeneous traffic, which contains different data flows of 2 different traffic classes. For each flow of a class its duration is chosen according to a

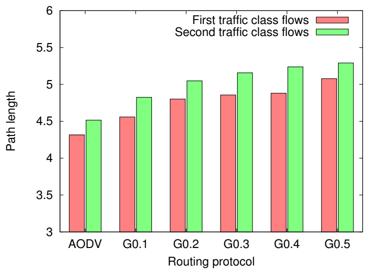


Fig. 9. Simulation results: average path length

TABLE I
DELIVERED PACKETS PERCENT

	CAM-MAC	CAM-MAC ARCB
AODV	63.1577	69.1456
Gradient routing (0.2)	71.8319	80.5288

TABLE II
RCB RATE (CASES PER NODE PER SECOND)

	CAM-MAC	CAM-MAC ARCB
AODV	4.8324	0.0038
Gradient routing (0.2)	5.9265	0.0047

Poisson process whose mean value is defined by the class. Senders and receivers for the flows are chosen randomly. The first class defines flows of 75 Kb/s with a mean duration of 100s, while the second class defines flows of 37.5 Kb/s with a mean duration of 5 s. Fig. 8 and 9 present the result comparison for different protocols in a scenario where nodes form 2 flows of the first class and 3 flows of the second class. Fig. 8 and 9 present results for flows of both classes separately. During the simulation a node generate flows of different classes, which allows the node to simulate a mixture of different traffic requests. Each node has a single transceiver which operates with 1 control and 3 data channels with a maximum link speed of 2 Mbps. Each network node has a packet buffer which allows a packet to stay in a queue no longer than 100 ms. Results obtained from the simulation are averaged over 20 simulation runs. The performance evaluation metrics includes: average delivered packets; average number of hops each packet travels between the source and destination; and the average route ability. For each route established, the "route ability" is defined as the minimum of values for nodes abilities (as described in Section V-B). Therefore, the average route ability is the averaging of routes for all established flows.

Fig. 8(a) presents results for the successful average number of packets delivered for two different flow types. As the results shows, using the load estimation mechanism for guiding the route discovery improves the performance by nearly 10 percent in comparison to AODV. The results show that with a slight inclusion of load information, the performance increases and has a reasonable constant performance for different values. The flows of the second traffic class have less durations than flows of the first traffic class. Thus, frequency of the second traffic class flows changing is higher than the frequency of the first traffic class flows. The results show that the inclusion of the load information for routing shows more stabilized performance than the first traffic class. Therefore, this means that our solution is more stable for short duration flows. This is also reflected in the average route ability (Fig. 8(b)), where the first traffic class has higher fluctuations when the values increase. However, the performance still outperforms pure AODV based routing. Fig. 9 presents value for the average path length for the second traffic class. As shown in the figure, the flows with higher weighting on node load will result in longer paths, since the path discovery will avoid loaded parts of the topology.

Tables I and II present performance comparison for different combinations of channel allocation layers (CAM-MAC, CAM-MAC-ARCB) and routing protocols (AODV, Gradient routing). The Gradient routing protocol uses γ of 0.2. Simulations are conducted for traffic scenarios with two flows of the first class and three flows of the second class. Again the simulation is performed for a topology of 96 with an average node density of 9. As shown in Table I, since CAM-MAC protocol doesn't consider "redundant channel blocking" problem (RCB cases ([11])) its performance is lower than the CAM-MAC (for both AODV and Gradient routing combination). The best performance is from the CAM-MAC-ARCB in combination with gradient based routing. The RCB rate in Table II, presents the average number of redundant channel blockings and we can see that the CAM-MAC-ARCB has the lowest when compared to CAM-MAC in combination with the two routing protocols.

VII. CONCLUSION

As the popularity of ad hoc networks increases, researchers are investigating new avenues for more efficient protocols for devices. One approach taken is to lower the hardware costs (e.g. devices equipped with single transceivers) and increasing capabilities of software protocols. This has been reflected in various research works on cooperative multi-channel MAC protocols. In this paper we have developed a new routing protocol to support multi-channel MAC protocols. The proposed solution is based on our extended version of CAM-MAC, known as CAM-MAC-ARCB [11], and incoporates the gradient based routing for multi-hop transmission. The approach improves the load balancing of the network and improves the overall throughput performance of the network. Simulation work have also shown that the gradient based routing outperforms standard AODV routing protocol when integrated with both types of cooperative multi-channle MAC protocols.

ACKNOWLEDGMENT

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Appendix C:

"Cooperative Wireless Sensor Environments Supporting Body Area Networks"

Cooperative Wireless Sensor Environments Supporting Body Area Networks

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***Abstract*—Wireless Body Area Network (WBAN) in recent years have received significant attention, due to their potential for increasing efficiency in healthcare monitoring. Typical sensors used for WBAN are low powered single transceiver devices with a single channel for transmissions at the MAC layer. However, these devices usually lead to performance degradation when the density of sensors increases. One approach to counter this performance degradation is through cooperation at the MAC layer for multi-channel devices. In this paper we propose a cooperative WBAN environment, where sensors within the environment as well as WBAN are able to cooperate to support multi-hop transmission. Our solution extends the cooperation at the MAC layer to a cross-layered gradient based routing solution. The solution allows interaction between WBAN and environmental sensors, where the environmental sensors are also able to transmit data from WBANs to a distant gateway. Extensive simulations for healthcare scenarios have been performed to validate the cooperation at the MAC layer, as well as the cross-layered gradient based routing. Comparisons to other cooperative multi-channel MAC and routing solutions have shown that the proposed approach improves the overall performance (e.g. packet loss, power consumption, delay).**

***Index Terms*—Body Area Networks, Multi-channel MAC Cooperation, Gradient Based Routing**

I. Introduction

Monitoring human health through Wireless Body Area Networks (WBAN) has received tremendous attention in recent years. Their ad hoc nature and ability to provide continuous patient monitoring makes WBAN applicable to a vast number of scenarios ranging from hospital care [1] to emergency response, and humanitarian relief efforts [2], [3]. Typically, a WBAN consists of a sink unit and several number of wireless sensors, which could be either worn externally (e.g. sensors implanted on garments) or implanted into the body. The sensors continuously measure diverse physiological parameters, which typically includes ECG, blood oxygen level, body temperature and pressure, etc. Obtained measurements are communicated to the sink which aggregates the sensor readings and may in turn transfer them to an external computing entity (e.g. monitoring server in a hospital). Using such systems can allow health monitoring of better quality at lower costs, and thus their utilization is highly beneficial for various care providers.

In recent years, numerous research studies have been conducted in wireless sensor networks. Examples of solutions for wireless sensor networks include data dissemination [4] and energy efficiency [5] [6]. While WBAN provides an opportunity for close monitoring of patient conditions, it also brings along a number of new challenges. Firstly, the ability to extract and transmit this data efficiently to the remote server. Secondly, how could such WBAN networks interact with the sensor networks that are found in the environment, where these sensors may also monitor the environmental condition. While the first challenge has been addressed through solutions that allow sensors on WBAN to transmit information to external WiFi access points, this could lead to excessive energy dissipation. The second challenge brings along a few capability, where cooperation between WBAN as well as sensors in the environment, can allow cooperation to be performed at different levels. This could provide new opportunities for WBAN to not only be limited to gathering information from the sensors on the body, but also to interact with information from the environment that could be beneficial to analyzing the patient's condition.

The aim of this paper is to propose an efficient cooperative algorithm between WBAN and environmental sensors. In particular, the focus will be placed on the ability for the environmental sensors to deliver information from WBAN, neighboring environmental sensors or other wireless monitoring devices (e.g. wireless video) to a gateway. We assume that all these sensor devices are single transceivers with multiple data channel and single control channel. The cooperation technique proposed in this paper will be at the MAC layer, and extends to a cross layered solution that incorporates gradient based routing at the IP layer. The cooperative process between the sensors can also allow different gradient routes to be set up for WBAN patients with different conditions (e.g. patients in critical conditions will have data routed through better paths than stable patients). Comparative simulation studies of our healthcare scenarios have also been conducted with other cooperative techniques, and has show to improve the overall performance (e.g. packet loss, power consumption, and delay).

The paper is organized as follows: Section 2 provides the related work. Section 3 provides an introduction to the WBAN cooperative environment, while section 4 presents the cooperation at the MAC layer, and section 5 describes the gradient based routing. Section 6 describes the simulation work, and lastly, section 7 concludes the paper.

II. Related work

In this paper, we will present two important related works that is crucial towards our proposed solution, which include cooperation at the MAC layer, as well as Body Area Networks.

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A. MAC layer cooperation

Since WBAN devices are usually designed as low powered miniature devices, we believe that this underlying communication is best suited for single half-duplex transceiver devices. Single transceiver devices are equipped with multiple data channels and single control channel. Once a node is tuned to a data channel, it is able to either transmit through or receive data from the channel, but at the same time the node has no capability of learning about current unused channels. Therefore, cooperation is usually required to provide knowledge on currently used channels to neighboring nodes, to minimize data collisions from communicating on the same channel. Typically, cooperation is performed through negotiations in the control channel, and after a successful negotiation process, the nodes will communicate on the same data channel. Viadya [8] proposed the Multi-channel MAC (MMAC) protocol, which enables data transmission scheduling performed by neighboring nodes in predefined time intervals of fixed length. Maheshwari et al [9] presented an extension of the MMAC protocol that allows varying the interval's length, while further enhancements by Cordiero and Challapali [10] enabled dynamic control of channel selection. However, the proposed scheduling technique requires the interval to be able to accommodate all possible neighboring nodes, which could result in increased interval duration. This is not suitable for pervasive healthcare environment, which maybe composed of large number of sensor nodes.

Shi et al. [11] proposed a solution where negotiations between nodes can be overheard by neighbouring nodes, which could use this information to achieve better collision avoidance. However, to allow each node to have full knowledge of negotiations between their neighbours, each node would be refrained from data exchange for a certain period of time. This, in turn increases packet transmission delay, which is not ideal for WBANs that may require timely data delivery. A similar approach was proposed by Kuang and Williamson [12] for cooperation that supports reservation of bi-directional nature of TCP/IP traffic. In order to maximize full knowledge of channels negotiated by the neighbours, Chen et al. [13] proposed each node to be equipped with an additional transceiver solely dedicated to listening on the control channel. Similarly, Nguyen [14] proposed device hardware enhancements, where each device has an additional busy tone transmitter. However, these solutions are not ideal for WBAN systems that have resource constraints.

Luo et al [15] [16] [17] proposed the Cooperative Asynchronous Multichannel MAC (CAM-MAC) protocol, which is a cooperative technique where the channel availability information is provided to the entire neighborhood rather than individual selected nodes. Each node also has the capability to veto negotiations of invalid channels performed by neighboring nodes. Ivanov et al [18] further extended Luo et al's solution by minimizing Redundant Channel Blocking (RCB) problem. Another extension considering energy efficiency of CAM-MAC is presented in [19], where specific altruistic nodes perform the major part of the information collection, and thus allow the remaining nodes to reduce their energy expenditure by having a longer sleep state.

B. Body Area networks

Typically a wireless health monitoring sensor system adopts WBAN design specified by the IEEE 802.15.4 standard [7]. The standard specifies low data rate and power transmissions carried over short distances, which normally do not exceed 10m. Each node is equipped with a single half-duplex IEEE 802.15.4 transceiver that could be tuned to any one single channel from a total of 16 available channels. Therefore, a common problem is when WBAN node shares the same channel with other nodes located within its transmission range, which leads to performance degradation in cases of high density of nodes. Such degradation may compromise the monitoring process resulting in unreliable data transmissions. In [20] Hanson et al. discussed the opportunities and challenges of Body Sensor Networks. While these opportunities can provide opportunities for new application domains, such as healthcare and entertainment, there are still a number of challenges. These challenges includes, (i) providing maximum value to end users, (ii) providing safety, security, and privacy for the end user, (iii) enable compatibility as well as ease of use for end users. Han and Park [21] presented another challenge in the practical use of Body Area Sensor networks, where the wireless communication to the access point is affected by the movements of the body, in particular the bit-error performance. Quwaider and Biswas [22] also evaluated a number of different Delay Tolerant Network routing algorithms based on the posture of the user with Body Sensor Networks. The authors presented a solution based on multi-scale modeling of spatio-temporal locality of link disconnection patterns which provided the best routing performance. A major problem with WBAN is multiple access interference that could be caused from transmission of short range sensors. In [23] Kim et al. presented a solution that minimizes this problem through the use of binary zero correlation data for ultra wide band systems used in WBAN. This coding process has shown to improve the performance of minimizing interference.

While numerous works have been focused on MAC layer cooperation, as well as WBAN, very limited work have focused on how interactions can be achieved between WBAN and environmental sensors, and how such environmental sensors can handle loads of heterogeneous traffic from multiple sources In particular, how routing process within the environmental sensors can handle different priority of WBAN traffic, which is the problem that this paper will be addressing.

III. Cooperative WBAN environment

Our scenario of a cooperative WBAN environment is illustrated in Fig. 1. As illustrated in the figure, we envision an environment that is composed of dense wireless devices that includes environmental sensor networks (these sensors may also include wireless video), as well as a number of users, each with WBANs. The environmental sensors networks are multipurpose sensor nodes that are able to, (i) sense various environmental conditions (e.g. dust, temperature), and (ii) route packets on behalf of neighboring devices, including from

WBANs. Therefore, as illustrated in Fig. 1, the cooperation process can occur between different WBANs, between WBAN and environmental sensors, or even between the environmental sensors.

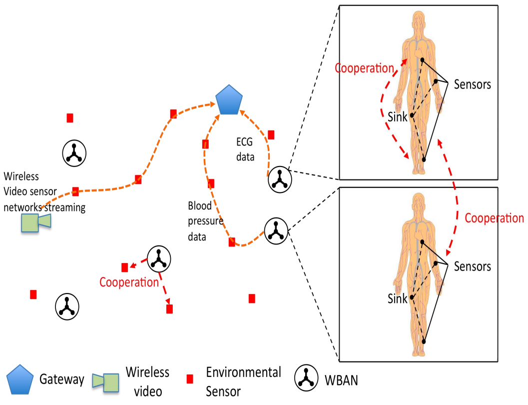


Fig. 1. Cooperative WBAN environment

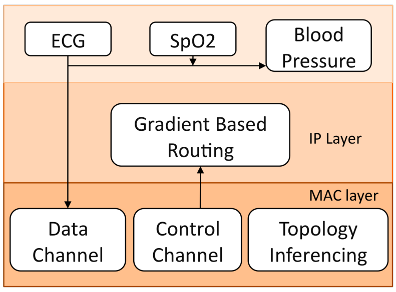


Fig. 2. Proposed solution for Integrated Gradient Based routing and Cooperative MAC layer supporting WBAN

Our aim is to develop a solution that enables cooperation to be performed between the sensor nodes, where this cooperation can support multi-hop transmission of information to a dedicated gateway. This would lead to a situation, where multiple traffic types will be streamed through the sensor networks, requiring the sensor nodes to cooperate and self-organize and adapt to varying traffic load (e.g. as WBAN users move between locations or as patient's condition changes). The streaming process should also be different for patients with different conditions and criticality. Our proposed approach is based on a cross-layered solution, depicted in Fig. 2. In particular, our solution is based on cooperation at the MAC layer, which consists of multiple data channel and single control channel. A protocol known as CAM-MAC-Avoiding Redundant Channel Blocking (CAM-MAC-ARCB) [18], which extends the original CAM-MAC protocol [17], has been developed to efficiently and reliably cooperate to maximize data transmission. This cooperation will also extend to the IP layer, to provide information on loads of sensors within the environment, where this information is then used to route data using gradient based routing. Through this cross-layered process, sensor devices should be able to transmit various types of traffic, and also consider the criticality of the data type (e.g. patients with severe conditions should have higher priority). Our motivation of proposing this solution is as follows:

1) Provide an approach to allow WBAN to interact with the sensors within the environment. This will provide an opportunity for WBAN to coordinate information collected from the body as well as the environment, which could be beneficial to numerous pervasive healthcare applications.
2) Provide an infrastructure that could be used to route traffic from multiple sources, including WBANs. This solution also minimizes requirements of installing WiFi to collect data from WBAN.

In the case of (2), the interaction between WBAN and the environment sensors will also limit the energy expenditure from the sensors on WBAN, compared to transmitting to a WiFi access point. We will first begin by describing the CAM-MAC-ARCB solution in the next section, while the following section will show how this has been extended to incorporate gradient based routing.

IV. CAM-MAC-ARCB

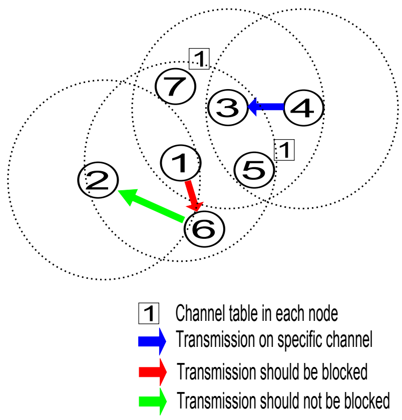
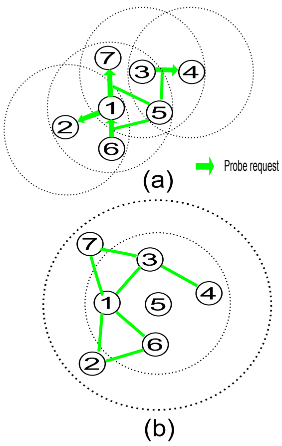


Fig. 3. Redundant channel blocking in CAM-MAC protocol

The related work section presented research on cooperative MAC layer, and one proposed solution was the CAM-MAC protocol. The advantage of CAM-MAC is in its ability to monitor and assist fellow neighboring nodes during the negotiation process, which is essential for WBANs to reliably transmit packets. While the protocol does provide assistance in vetoing negotiations made by other nodes in the control channel, the one issue with the protocol is the propagation of channel information to distant nodes which could prevent the nodes from using specific channels even if the nodes using those channels are not in range. We refer to this phenomenon as the RCB problem. In order to counter this problem, we developed the CAM-MAC-ARCB solution, which avoids unnecessary blocking of valid channels.

Fig. 3 illustrates an example of this problem. In this example, node 3 and 4 are communicating on a specific channel. During the negotiation process between 3 and 4, nodes 5 and 7 were in range and overheard this negotiation process, and records the valid channel available in that environment. However, with the current CAM-MAC protocol, if node 6 initiates a negotiation process, and selects a channel that is the same as that used by nodes 3 and 4, they will be vetoed by 5. This leads to node 6 not being able to use the channel even though both node 6 and its receiver are out of range of nodes 3 and 4. This problem reduces the overall throughput of the network due to unnecessary prevention of channel usage, resulting from improper propagation of knowledge. In order to counter this problem, we incorporated topology inferencing, where each node is able to sense used channels and their respective range based on a virtual topology [18]. The virtual topology inferencing process is illustrated in Fig. 4.



Level 1	Level 2
3(1,4)	7
4(3)	
6(1)	2
1	2, 7, 6
...	...
...	...

(c)

Source	Destination	Duration
3	4	1
1	2	2
...	...	...
...	...	...

(d)

Fig. 4. (a) Node 5 sending neighbors probe request, (b) virtual topology inferencing, (c) virtual topology table by node 5, and (d) channel table of node 5

In this particular example, we focus on node 5 that is listening to the neighbors' negotiation process. During the negotiation process, each node transmits in its control session a probe request, which contains the source and destination address, and the requesting channel. Each node will create a table that categorizes each neighboring node as either in Level 1 or 2. Level 1 indicates that the node is an immediate neighbor, while Level 2 indicates the node is a neighbor of a neighboring node (Fig. 4(b)). Fig. 4 (c) illustrates the virtual topology table, while Fig. 4 (d) illustrates the table of channels used by the neighboring nodes.

Coming back to our example in Fig. 3, while node 5 records the information of nodes 3 and 4 transmitting on channel 2, node 6 and 1 will be the only nodes to be blocked by node 5 from using channel 1. This in turn will allow nodes to increase their transmission capabilities compared to the CAM-MAC protocol. More details on the virtual topology inferencing process can be found in [18].

V. Cross-layered Gradient Based Routing

As described in section III, our approach is based on a cross-layered solution that could enable the WBAN and environmental sensors to use the cooperation at the MAC layer to support multi-hop packet transmission. In this section, we will describe how we built a gradient based routing process over the CAM-MAC-ARCB cooperative technique. The proposed solution will result in gradient-based routes that traverses through lightly loaded parts of the networks. Implicitly, the solution will support more efficient scheduling and improve the overall performance by providing timely delivery of data from WBANs. We will also present in our simulation work, that we could use this to differentiate between different traffic classes of WBAN data. The next section will describe the load sensing process, which is cooperatively performed by the nodes and their immediate neighbors.

A. Impact of load fluctuations

We will first define the load that each node can support. An example of the load sensing process is presented in Fig. 5.

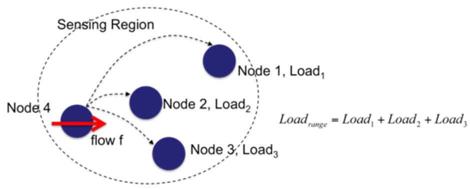


Fig. 5. Illustration of load sensing

Each node contains data channels, and since each node is equipped with only a single half-duplex transceiver and only one data channel can be used at any one time, this leads to each node having an upper bound of maximum load that cant exceed $1/n$. Thus, for each node i, $0 \leq Load_i \leq 1/n = Load_{max}$.

We will now describe the $Load_{Range}$ based on the example of Fig. 5. Node 1, 2, and 3 are within the sensing range of Node 4, which collects the load information from these nodes. In the event that a new data flow f is to be routed through a node i, this will lead to an increase in the load of the node $(Load_f)$, as well as the range. Therefore, the new load can be represented as: $Load_i^{new} = Load_i + Load_f$, and the $Load_{Range}^{new} = \sum_j Load_j^{new} = \sum_i Load_i + Load_f$.

The calculation above will lead to a new bound for the additional load, which could be represented as a range for node i, where $0 \leq Load_f$ and $Load_f \leq NC_i$. Therefore, $NC = min(1-Load_{Range}; Load_{max}-Load_i)$, where NC_i describes the capacity of node i to route new flows. In the following section, an asynchronous autonomous cooperation technique for estimating values of node capacity will be presented.

B. Node Capacity Estimation

The estimation of node capacity is essential for maximizing the throughput for multi-hop packet transmission. Fig. 6 illustrates our node capacity estimation process.

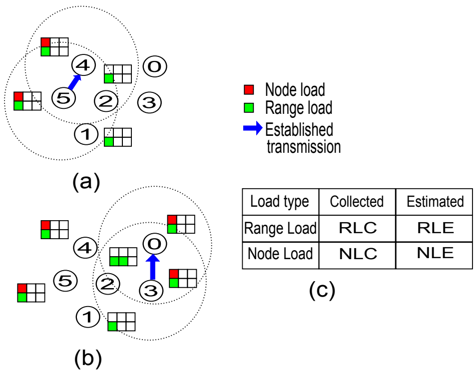


Fig. 6. Extension of MAC layer cooperation for load estimation

As illustrated in Fig. 6 (c) each node contains a table with two values which includes the Range Load Collected (RLC) and the Node Load Collected (NLC), where these values are updated in set intervals. The RLC is used to sense the loads of neighboring nodes. Each time a node becomes involved in a successful negotiation, the node updates the RLC value (based on the process presented in Section V.A). In case the node is the sender or the receiver of the negotiation, it also updates the NLC value. The process of load estimation is illustrated in Fig. 6 (a)-(b), where the NLC and RLC are represented as red and green bars, respectively. In this example, we illustrate two data flows that are initially transmitted from node 5 to node 4, and a short time later from node 3 to node 0. For each transmission, we limit the packet transmission to a maximum of 3 packets (therefore, 1 packet transmission is equivalent to 1/3 additional load). Initially, nodes 5 and 4 performed a negotiation process, which was supported by nodes 1 and 2. Following the successful negotiation, nodes 5 and 4 start to transmit 1 packet. Therefore, based on this successful transmission and negotiation, the updates of the RLC and NLC cells are as follows: Nodes 1, 2, 5 and 4 add 1/3 to their RLC cells and nodes 5 and 4 add 1/3 to their NLC cells. Once this is complete, node 3 successfully negotiates to transmit to node 0, and this was supported by node 2 (Fig. 6 (b)). Following the successful transmission of 1 packet from nodes 3 to node 0, the following updates to the table is performed: nodes 0, 2 and 3 add 1/3 to their RLC cells; and nodes 0 and 3 add 1/3 to their NLC cells. As shown in Fig. 6 (b), the range load within the sensing region of node 2 starts to increase after the two transmissions, which indicates the load of that region has increased due to transmission from two independent pair of nodes.

The load table in Fig. 6 (c) also includes the Range Load Estimation (RLE) and the Node Load Estimation (NLE), which predicts values of the future range and node load. The prediction technique is based on exponential averaging of historical values that were collected. The calculated NLE and RLE values are used by the node to determines each node's own routing capacity. Therefore, for node n, the $Load_n = (1-\beta) \cdot NCL + \beta \cdot NLE$ and the $Load_{Range} = (1-\beta) \cdot RCL + \beta \cdot RLE$.

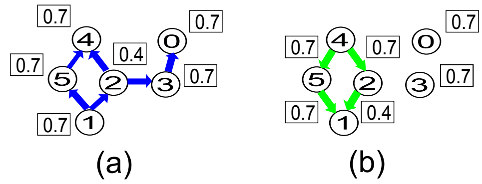


Fig. 7. Routing and load estimation

Fig. 7 (a) illustrates the NC_i values for the scenario of Fig. 6. For this example, we have set the exponential smoothing factor (β) to 0.1. Since node 2 was the node that collected the values from neighbours within its range, we demonstrate these values from the perspective of node 2. We assume an initial value of 0 for NLC, and the RLC value is 2/3. Therefore, by including the values of the predicted and current load estimation, the value of $Load_2$ is 0, and $Load_{2,Range}$ is 0.6.

As described earlier, nodes in the example use a single data channel for data transmission. Therefore, since $Load_{max} = 1/1 = 1$, and since $NC_i = min(1 - Load_{Range}; Load_{max} - Load_i)$, this would lead to $NC_2 = min(1-0.6; 1-0) = 0.4$.

C. Gradient based routing

In this section, we will present the mechanism of using the NC_i values calculated in the previous section to determine the gradient based routing process. In our proposed solution, the routing process determining the path that traverses through nodes with maximum NC_i by creating a gradient field within the environment. The gradient function is adopted and modified from our previous solution in [24], and is represented as,

$$G_{n,d,n \to i} = \gamma \cdot \Phi_{i,d} + (1-\gamma) \cdot h_{i,d}, \quad (1)$$

where, the Φ represents normalized NC_i for node i to destination d, and $h_{i,d}$ represents the normalized hop count to destination d. The assumption of our proposed solution is that each node is aware of their hop count value to the destination gateway, and is normalized with respect to all nodes within the environment. An example of proposed gradient based routing technique is illustrated in Fig. 7. In the event that node 1 wants to send a packet to node 4, it initiates a route discovery process, which is illustrated in Fig. 7(a). The discovery process will broadcast the discovery packets to all available paths towards the destination gateway. The aim here is to select the most appropriate path to the gateway. In our example, the source node (node 1) has an option of two routes, where one goes through node 5, while the other goes through node 2. Although both paths have the same hop count value, the capability of node 5 is better, and is, therefore, selected due to the higher gradient value. By selecting node 5 as the next hop, data flow 1-4 goes through the route where it competes only against the flow going from node 5 to node 4. However, the situation would be different if node 2 was selected, since the data flow 1-4 would have to compete with both data flows transmitted from nodes 5-4 and 3-0. Once the discovery packet reaches the gateway, it retracts its path back to the source, which is illustrated in Fig. 7(b).

VI. Simulations

In order to validate the proposed solution extensive simulation was conducted, using a Java based event driven simulator. The simulation section is sub-divided into three sections, where section VI (A) evaluates the CAM-MAC-ARCB, section VI (B) evaluates the cross-layered gradient based solution, and section VI (C) evaluates the performance for a scenario with patients of varying criticality.

A. Performance of CAM-MAC-ARCB

The aim of this simulation is to compare the channel allocation performance between CAM-MAC-ARCB, CAM-MAC, and Zigbee (IEEE 802.15.4) sensors from a WBAN perspective. The scenario for the simulation, illustrated in Fig. 8, is a hospital waiting area where patients are equipped with WBAN are seated in close proximity to each other.

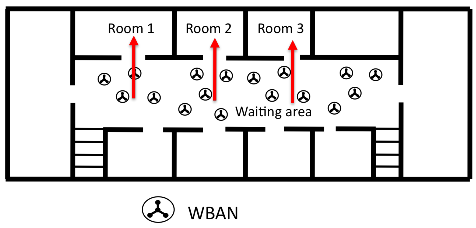


Fig. 8. Hospital waiting area floor plan with WBAN patients in waiting area

The parameters used for the simulation are presented in Table I. There are 3 rooms (5m x 5m), each with a specialist that calls a patient in one at a time. This may lead to a high density of patient at specific points, which also leads to high interference during channel allocation. Our aim is to evaluate the inferencing process during the cooperation, and to evaluate the RCB and its influence on the network performance at the MAC layer. Simulation results are averaged over 20 independent runs and each run models 20 minutes of monitoring time. Fig. 9 presents the ratio of successfully delivered packets with respect to the number of patients.

As shown in the graph, the performance degradation in case of the single-channel MAC protocol proposed by the Zigbee sensors, becomes noticeable after 10 patients. However, both the CAM-MAC and CAM-MAC-ARCB protocols show good performance for higher number of patients.

TABLE I
Simulation parameters

Parameters	Value
No. of sensors on WBAN sensors on WBAN	6 (4 ECG patches, an accelerometer, and sink)
Sensor Transceiver	CC 2420 (1 control, 3 data channels)
Capacity	0.2 Mbps
Transmission range	7m
Power consumption	Transmission (33mW), reception (56.4mW), sleep (1.27mW), idle (0.06mW)
ECG measurements	200 bytes/s
Accelerometer	50 bytes/second

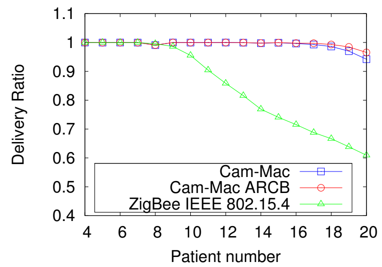


Fig. 9. Successful packet delivery ratio

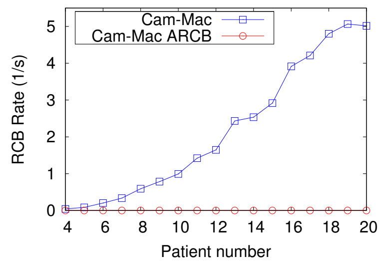


Fig. 10. Rate of redundant channel blockings

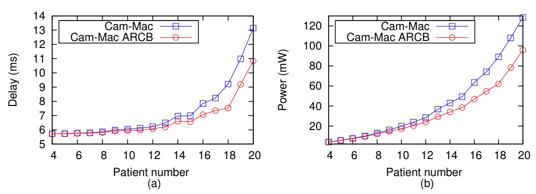


Fig. 11. Packet transmission delay (a) and aggregate power consumption of the WBAN sensor nodes (b)

Fig. 10 presents the RCB Rate with respect to patient

TABLE II
SIMULATION PARAMETERS

Parameters	Value
No. of Patients	5 - 25
WBAN Gateways	6
Environmental sensors	56
Wireless video camera	8
Video transmission rate	35 Kb/s
Patient inter-arrival time	10s
Accelerometer	50 bytes/second

numbers. As each WBAN monitoring system contributes the same amount of traffic load; with the increase in number of patients, the load created by the WBAN transmissions increases as well. This, in turn, leads to an increase in simultaneous transmission of different sensors, which degrades the CAM-MAC performance. Besides the increase in RCB rate, the increase in patient numbers also leads to increase in packet transmission delay (Fig. 11 (a)) and power consumption (Fig. 11 (b)). The power consumption for CAM-MAC is higher due to each sensor having to remain awake for longer period of time. The results has shown the effectiveness of inferencing and learning the positions of the sensors during the negotiation process, allowing increase throughput for all WBANs.

B. Performance of Cross-layered solution

This section presents the performance results of the gradient based cross-layered solution in comparison to the AODV routing algorithm. The scenario for this simulation is illustrated in Fig. 12, where we simulate an environment that is composed of environmental sensors, gateways and WBANs. The WBANs would transmit data to a sink (also part of the WBAN), and the sink would transmit its data to the gateway through the environmental sensors. The parameters used for the simulation is presented in Table II.

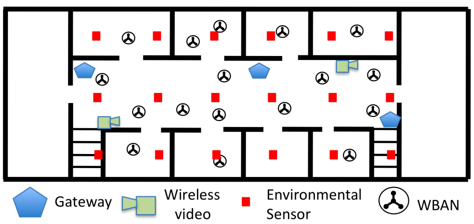


Fig. 12. WBAN patients wireless environment of sensors

In this scenario, patients are slowly increasing in a hospital waiting hall size of 49 x 28 meters. Initially, no patients are in the room and all the traffic delivered to the gateways are transmitted from the wireless cameras and environmental sensors. Therefore, the video transmission represents the background traffic that the WBAN traffic needs to co-exist with. As time passes, the number of patients slowly increases, where they will walk in and randomly position themselves inside the room during the simulation. The patients' inter-arrival interval is every 10s. The γ value selected for the gradient based simulation of equation (1) is 0.2 (Gradient (0.2)) and 0.4 (Gradient (0.4)). We selected these two different values to evaluate the performance with different weight settings. Fig. 13 presents the overall undelivered packet ratio for all the three protocols. As confirmed in the results, the proposed cross-layered solution with both 0.2 or 0.4 γ values, outperforms the AODV protocol, where γ of 0.4 shows the best performance. The reason for this is because of the capability of the proposed solution to detect and avoid highly loaded sensor network regions when transmitting data from WBAN or video sensor.

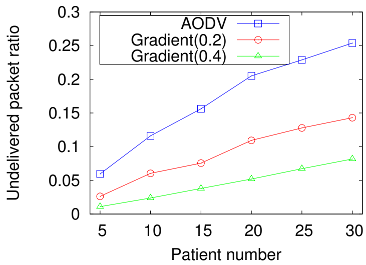


Fig. 13. Gradient based routing evaluation - ratio of packets undelivered to the gateways

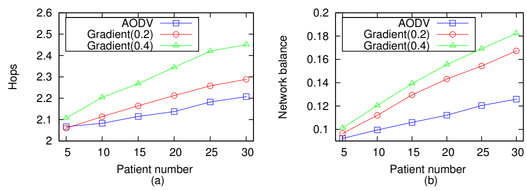


Fig. 14. (a) average number of hops travelled by a data packet, (b) and network balancing

Using a higher γ coefficient increases the reactivity of the routing process to the load already existing in the network (e.g. video traffic). This in turn leads to creation of longer routes by new flows from WBAN and improves the load balancing across the entire network. Fig. 14 (a) presents the results for the average number of hops travelled by a data packet delivered to a WBAN gateway. Fig. 14 (b) presents the network balancing values as the number of patients increases. A higher value for network balancing demonstrates improved performance, and is calculated by equation (2), where x_i is the number of packet forwarded by node i, and N is the total number of node.

$$Network\ Balancing \quad = \quad \frac{(\sum_i x_i)^2}{N \cdot \sum_i x_i^2}, \qquad (2)$$

C. Varying patient criticality

While the previous section considered cross-layered soluton for homogeneous traffic behaviour, this section concentrates on mixed traffic classes to reflect different patients' condition. In

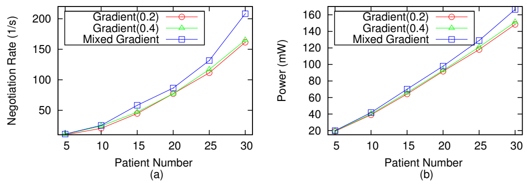


Fig. 15. (a) Rate of negotiations for WBAN sensors, (b) total energy expenditure of WBAN sensor nodes

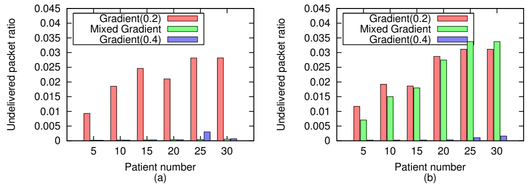


Fig. 16. (a) packets undelivered to the remote gateways for critical patients, (b) packets undelivered to the remote gateways for stable patients

TABLE III
VARYING γ FOR DIFFERENT PATIENT CONDITION

Parameters	γ	Quantity (%)
Critical	0.4	30
Stable	0.2	70

particular, patients in critical conditions should require timely delivery with higher reliability than stable condition patients. The aim of this simulation is to determine how efficiently the data packets from WBAN are transmitted over the environmental sensors, and the type of paths they take when different γ values are used. In the case of mixed gradients, we allocated γ as 0.2 for stable patients and 0.4 for critical condition patients. Fig. 15 (a)-(b) presents the simulation result for aggregate number of neighbour negotiations and energy consumed by all WBAN sensors. The mixed gradient solution tends to increase the number of negotiations for the WBAN sensors, and also the energy, and this is due to the route being highly diverted for data streams from critical patients. However, Fig. 16 (a) and (b) shows the underlivered packets ratio, which shows that the mixed gradient data packets have the lowest losses. The undelivered packets for critical patients of Gradient (0.4) is very close to mixed gradient, however the loss increases dramatically for stable conditions patients.

Additionally Fig. 17-18 present the overall network balancing, rate of negotiations, and power consumptions for the WBAN sensors with respect to time. In this simulation scenario, there are 30 patients in the room, and the simulation parameters are from Table II. Initially, the room is empty, and patients will slowly start walking into the room, where the last patient will enter at 5.5 minutes. As predicted the Gradient 0.4 exhibits the best network balancing, since the packets are evenly spread across all the nodes, with mixed gradient performing the worse, since stable patients will take shorter paths and load certain nodes heavily, compared to the critical patient data traffic, which will spread evenly in the remaining nodes. The behaviour of the network balancing, is also reflected in the number of negotiations (Fig. 18 (a)) and power-consumption of the WBAN sensor nodes (Fig. 18 (b)). Once the network stabilizes, the mixed gradient performance is in between the Gradient (0.4) and (0.2), which is also the same for the power consumption.

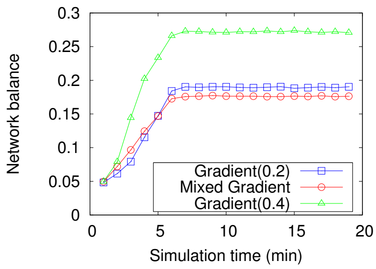


Fig. 17. Overall network balancing with respect to time

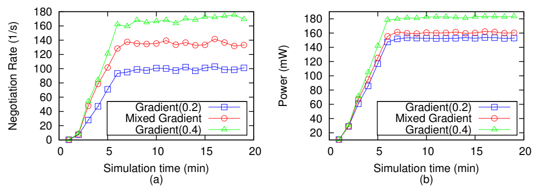


Fig. 18. (a) rate of negotiations for WBAN sensor, (b) WBAN sensor nodes power consumption with respect to time

VII. CONCLUSION

Wireless Body Area Networks (WBAN) provides a new opportunity for monitoring healthcare patients in an efficient and cost effective manner. Such devices in the future could potentially be provided as everyday consumer electronics for end users, allow healthcare providers to have more efficient techniques of monitoring patients. In this paper, we have proposed cooperation that could be performed by single transceiver devices that could exist in the environment or as WBAN. Our proposed solution is based on a cooperation at the MAC layer that is extended for cross-layered gradient based routing process. We have performed extensive simulations that evaluates the cases for MAC layer cooperation for large number of patients in close proximity, as well as evaluation of the cross-layered solution for patients in an environment embedded with environmental sensors. The simulation work has also demonstrated the flexibility of the cross-layered gradient based routing solution for patients with different critical conditions. The results from the simulation have shown improvements in performance compared to other cooperative MAC layer and routing solutions.

ACKNOWLEDGMENT

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Appendix D:

"Virtual Groups for Patient WBAN Monitoring in Medical Environments"

Virtual Groups for Patient WBAN Monitoring in Medical Environments

Stepan Ivanov, Christopher Foley, Sasitharan Balasubramaniam, *Member, IEEE,* and Dmitri Botvich, *Member, IEEE,*

***Abstract*—Wireless Body Area Networks (WBAN) provide a tremendous opportunity for remote health monitoring. However, engineering WBAN health monitoring systems encounters a number of challenges including efficient WBAN monitoring information extraction, dynamically fine tuning the monitoring process to suit the quality of data, and to allow the translation of high-level requirements of medical officers to low-level sensor reconfiguration. This article addresses these challenges, by proposing an architecture that allows virtual groups to be formed between devices of patients, nurses and doctors in order to enable remote analysis of WBAN data. Group formation and modification is performed with respect to patients' conditions and medical officers' requirements, which could be easily adjusted through high-level policies. We also propose a new metric called Quality of Health Monitoring (QoHM), which allows medical officers to provide feedback on quality of WBAN data received. The WBAN data gathered is transmitted to the virtual group members through an underlying environmental sensor network. The proposed approach is evaluated through a series of simulation.**

***Index Terms*—remote health monitoring, wireless body area networks, adaptive routing, node cooperation**

I. Introduction

The healthcare industry today is facing increased pressure due largely to the ever increasing population and reduced funding from governments. Therefore, various research initiatives have been set up to develop new solutions to help enhance and support more efficient and cost effective health care systems (e.g. [1],[2],[3]). One approach towards this is to enable more efficient monitoring techniques, which could provide various benefits, including: (i) examination of patients based on their criticality, which in turn enhances doctor's time efficiency in examining patients, and lowers queues in emergency rooms, and (ii) accurate monitoring of patients conditions and trends over a period of time. Wireless Body Area Networks (WBAN) provides an opportunity to allow monitoring with such capability and high precision. While numerous research efforts have been dedicated to developing solutions for WBAN, majority of these do not consider end-to-end solutions, and challenges may arise if such systems were practically deployed. These challenges include, the ability to extract information from WBAN and view this virtually between medical officers (Challenge (i)), the ability for medical officers to set requirements (Challenge (ii)), where these requirements can drive the operation of the sensors (e.g. gather ECG data for patient X, every 5ms; prioritize data from critical patients), and the ability for WBAN sensors to cooperate in a scalable and distributed manner to support the requirements of Challenges (i) and (ii) (Challenge (iii)).

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This paper proposes a solution that addresses the Challenges (i) - (iii). The overall architecture is separated into two parts. The first part is the Virtual Group Enabler (VGE), which allows virtual collaboration groups to be formed between patients, nurses and doctors (and possibly environmental sensors). These groups allow data from WBANs to be analyzed remotely by doctors, and nurses; the virtual groups can be modified and changed depending on the patients condition or requirements from the medical officers. The change in virtual group configuration can be easily adjusted through high level policies. Our envisioned scenario is an environment that is densely populated with sensors, where these sensors are networked and can allow WBAN and virtual groups to interact. To accommodate such interaction the underlying wireless technology not only has to provide a fast reliable connection, but also needs to be energy and cost efficient due to the necessity to accommodate large number of patients. Also the proposed system requires a certain degree of adaptability in order to be easily coupled with a policy management system, where the policy management system can handle high level changes that might be required by the medical officers. As standard approaches fail to satisfy these requirements, our solution uses a cooperative multi-channel MAC protocol with adaptive routing that will be presented in the second part of the proposed architecture. Optimization of such a technology requires complicated fine-grained tuning, which usual medical practitioners are not familiar with. Therefore, our proposed solution goes further by allowing the virtual groups to use policies to specify behaviour and cooperation of sensors both on WBAN and in the environment. Through high level policies, medical officers can adjust performance of the system in the event that quality of sensor readings are poor due to high losses. Our proposed approach has been evaluated through a series of simulations.

The paper is organized as follows: Section II presents the related work, while Section III presents the overall architecture. Section IV describes the Virtual Group Enabler architecture and corresponding policies, while Section V presents the wireless transmission technology. Section VI presents the simulation work, and lastly Section VII presents the conclusion.

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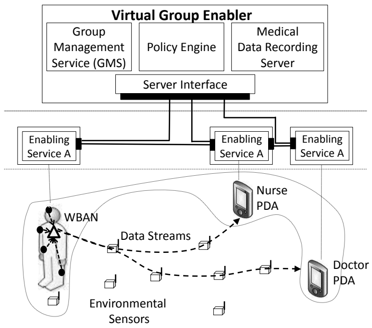

Fig. 1. Overall Virtual Group Enabling Architecture

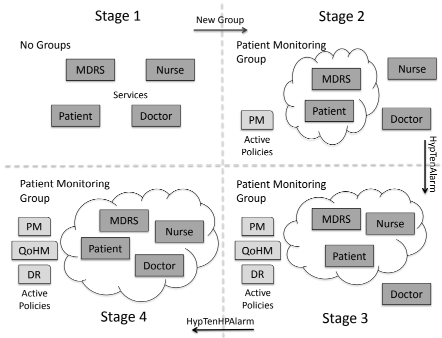

Fig. 2. Stages of Group Formation & Expansion

II. Related work

This section presents the related work in the area of Body Area Networks (BAN). A middleware for managing BANs is proposed by [4] which is underpinned by policy-based control. A common research in BAN is on how energy efficiency can be achieved at the sensor level, where in [5] a solution was proposed using localization and directional antennas. Bridging between physiological information sensed in a WBAN and a nearby WLAN is analyzed in [6]. Multi-patient monitoring is investigated in both [7] and [8], but the prioritization of different vital signs is not considered. An in-network solution to prioritize the transmission of patient vital signs for in-hospital triage using BAN was proposed in [9]. A cross-layer communication solution considering routing, medium access control and scheduling was proposed. A network architecture was proposed in [10] with multiple hierarchical tiers that illustrate three pervasive health-care applications. Appropriate security schemes were presented also in [10] for different wireless communications in the network tiers when privacy protection for individual health information is required.

While a number of solutions have provided approaches to accurately monitor patients, these solutions fall short with respect to a number of problems addressed in our paper. Firstly, current approaches do not support high-level polices that can translate down to re-configure sensors, in particular when the quality of the data delivered to the medical officers is affected by the congested sensor networks. Secondly, no metrics are provided to allow medical officers to provide feedback on quality of data in a human understandable language.

III. Overall Architecture

The overall system architecture is illustrated in Fig. 1, with the fundamental goal being to cluster or form groups that provide an efficient patient monitoring mechanism in the acute health-care field. Services run on each member's device within the group. The data gathered from the WBAN sensors on each patient is distributed to the group member's services. As illustrated in Fig. 1, our environment is densely populated with environmental sensors that provide data sources, as well as allowing WBAN to interact and deliver data between virtual group members.

The architecture of the VGE includes the Group Management Service (GMS), Medical Data Recording Server (MDRS) (which houses patients profiles), the Policy Engine (PE), and the devices of the medical officers, WBANs on patients, and environmental sensors.

GMS and PE combined provide the means to statically and dynamically build groups between any deployed services. It also provides a mechanism through which the behavior and management of these groups can be controlled, where this control is from a messaging process that is described in greater detail in [11].

IV. Virtual group Enabler

A. Group Management

Each Group instance is controlled by its own configuration and behaviour policy, where policies are developed from the concept of Policy Based Management Systems. Policies are used to handle groups under two different aims, (i) as an aid when configuring and building groups, and (ii) as a way to control the behaviour of a particular group. The policy has the following structure {*Event, Condition, Action*}. The *Event* element is an occurrence of an important message/incident that can be used to trigger the evaluation of Conditions. *Condition* is an aggregation of individual conditions which define the prerequisites for resulting actions, while *Action* represents the necessary actions which need to be taken if the Condition evaluates to true. When specific instances of the three are combined into one overall entity {*Event, Condition, Action*}, it is known as a PolicyRule, described in more detail in [11].

A reference representation of services within one single group and an example of its governing policies is specified in Fig. 2. This figure shows the different stages during group formation and group expansion. Stage 1 highlights the four different services that exist, with no groups formed. The transition to stage 2 is that a new Patient Monitoring (PM) group is formed between the Patient (with his/her WBAN) and the MDRS that is receiving all readings for historical recording of data. At this stage the PM policy is governing the group. A *HypertensionAlarm* is detected by the PM policy and this transitions the system to stage three where a nurse

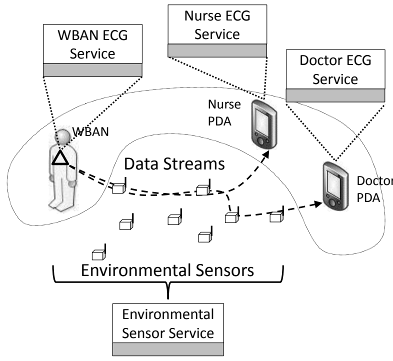

Fig. 3. Group Service Interaction via Environmental Sensors.

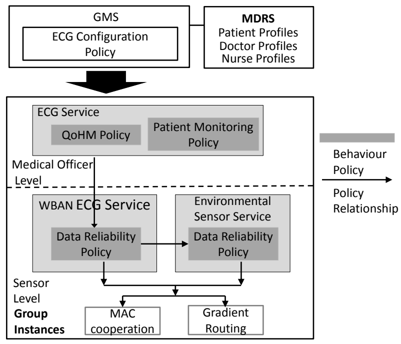

Fig. 4. An overall Group Instance Policy Perspective identifying the relationship to both MAC and Routing Technologies.

(N) is added to the group. Once this occurs the *Quality of Health Monitoring (QoHM policy)* policy and its related *Data Reliability (DR)* policy become active in the overall governance of the group.

The QoHM policy defines the perception quality that doctors or nurses have on the sensor readings presented on their device. The sensor readings maybe affected by packet loss along the data routes from the WBAN. Medical personnel can provide a QoHM level between 0 - 5 for each measurement type, with 5 being the highest quality. This is a similar concept to Mean Opinion Scores that are used to maintain Quality of Experience (QoE) for multimedia streaming [13]. The *HyperTensiveHighPriority* alarm is the event, which triggers the system into stage 4 and the inclusion of a doctor to the PM group. The listed policies governing the PM group are elaborated on in Section IV-C.

B. Deployment Perspective - Service and Policy

The application specific services deployed on each device are illustrated in Fig. 3. These service instances will become part of the patient monitoring group that in turn will be governed by different policies. The communication between the member's services will be performed through the environmental sensors, as shown in Fig. 3. Through these services and their inter-communication we address Challenge (i) of the introduction, namely the ability to share patient monitoring data between medical officers.

We selected this mode of communication over communicating via a wireless access point (e.g. WiFi) because; (i) access via WiFi from a mobile or sensor device could lead to higher energy consumption, (ii) environments will contain sensors which users of all types can interact with (an environmental sensor could also be a group member, in order to provide a richer data set), and (iii) this form of communication is distributed and has less single points of failure in comparison to WiFi access points. However, failures of environmental sensor nodes will only require new routes to be formed from neighboring sensors.

Fig. 4 illustrates in more detail the relationship between policies and deployed group instances in conjunction with the link to the underlying MAC and routing technologies. The context of the figure is ECG measurement. A group instance is created by issuing a request to the Group Management Service (GMS). The details of that group instance is stored in GMS for the lifetime of the group. Group creation allows for the assignment of one or more policies to the new group, where this mapping also resides in the GMS. The configuration policy determines the formation of the group by considering context profiles of each actor (e.g. a specific type of condition may require a particular specialist to join the group). The behavior policy impacts the run time actions that the individual members must take within the context of the group.

As illustrated in Fig. 4, the policies governing each group instance will have a hierarchical structure with different levels (medical officer levels as well as low level sensors). The Medical Officer Level contains policies that are associated with the patients within the groups (*Patient Monitoring policy*), as well as the *QoHM* policy. The *Data Reliability* policy is the governing policy at the lower sensor level. The combination of high and low level policies at the different levels underpins adaptive group behavior.

The formation of the group is based on the addition of a medical officer (e.g. nurse or doctor). The selection of which medical officer should be included over another (i.e. select nurse A over nurse B) is based on their load. The load in this case is defined as the number of patient monitoring groups that the medical officer is a member of. The medical officer involved in the smallest number of groups will be selected.

C. Specific Policy Logic

The Patient Monitoring (PM) policy, allows medical personnel to set thresholds on patient physiological data as well as allowing the administration of the patient monitoring group, e.g. adding or removal of medical officers depending on a patient's condition. An instance of this policy will exist for each patient. In order to present the policy in a readable format, we have provided example Policy Extracts (1, 2 and 3) in pseudo form. The actual policy syntax is primarily based on the TM Forum's Shared Information/Data Model Standard [12]. Fig. 5 presents a sample of a policy extract that is written in full syntax.

```
PolicyEventAtomic :
        {CommonName "ECGMeasurementEvent",
        EventIdentifier "ECG-MEAS",
        ParameterList "PatientIdentifier", "ECG-Value", "PatientID"}
PolicyConditionAtomic :
        {CommonName "HypertensiveAlarmCondition",
        Evaluate: PolicyStatement CommonName "" ,
        Variable "ECG-Value" Operator
        "GREATER-THAN" Value "400"}
PolicyActionAtomic :
        {CommonName "sendHypertensiveAlarm",
        ActionOrder 1 Enforce: PolicyStatement CommonName "",
        Variable "SendMsgToGroup" Operator "CALL" Value "Standard",
        "ECG greater than $ECG-Value "}
PolicyRule : {CommonName "RULE-ECG-HYPERTENSION",
                Priority "High", isTriggeredBy
Events
ref Policies.ECGMeasurementEvent,

containedPolicyConditions
Conditions
ref Policies.HypertensiveAlarmCondition RefersTo ref
Policies.ECGMeasurementEvent.ParameterList

containedPolicyActions
Actions
ref Policies.sendHypertensiveAlarm,
    executionStrategy DoAll,
    sequencedActions BestEffort,
    eventEvaluationScheme Any,
    conditionsEvaluationScheme And}
```

Fig. 5. Policy description example: complete syntax.

The *PolicyEvent*, *PolicyCondition* and *PolicyAction* defined in the syntax are stand alone definitions in their own right. The *PolicyRule* is the specification structure which constructs the associations between the instances of *Policy Events*, of *Policy Conditions* and of *Policy Actions* which determine the behaviour of the system. The rule specified in Fig. 5 is the full specification of PR(1) from Policy Extract 1. The following Policy Extract presents an example of the policy for Patient Monitoring:

```
Policy Extract 1.

PR(1): Event 'NewSensorData':
         IF (ECGValue is > 400)
           {sendMsgToGroup(HypertensiveAlarm);}
PR(2): Event 'NewSensorData':
         IF (ECGValue is > 450)
           {sendMsgToGroup
              (HypertensiveHighPrioirityAlarm);}
PR(3): Event 'HypertensiveAlarm':
         IF (!(GrouphHasMember == Nurse))
           {addMemberToGroup({MemberType, Nurse}");}
PR(4): Event 'HypertensiveAlarmHighPriority':
         IF (!(GrouphHasMember == Doctor))
           {addMemberToGroup({MemberType, Doctor}");}
```

The above policy extract specifies four rules; the first rule PR(1) extracts the *ECGValue* from the incoming sensor data and generates a *HypertensiveAlarm*, while PR(2) does a similar operation but generates a *HypertensiveHighPriorityAlarm*. The second two rules PR(3), PR(4) add an appropriate medical officer (a nurse for the *HypertensiveAlarm* and a doctor if it's a *HypertensiveAlarmHighPriority* event) to the group.

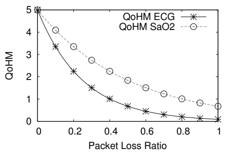

Fig. 6. QoHM for ECG and SaO2 patients readings

Once a nurse or doctor is added to the monitoring group, they have the capability of manually setting the desirable level of QoHM via the ECG service running on their device. This level is further used for performance assessment. As described earlier, the QoHM is adapted from Quality of Experience (QoE) metrics previously proposed for multi-media services. QoE quantitatively relates user perception, experience and expectation with network performance metrics. A number of studies have developed relationships between QoE and network performance metrics. For example in [13], the QoE (which is defined as Mean Opinion Score (typical user-subjective rating)) and its relation to the end-to-end packet loss metric is represented through a negative exponential function. This expression has been validated for the case of a generic streaming service, and hence presents an ideal candidate for our solution that will stream sensor data. The QoHM is assessed periodically by analyzing the loss ratio of data packets carrying sensor reading. The calculation of the QoHM is represented through the following equation:

$$QoHM \quad = \quad 5 \cdot exp(-w \cdot r), \tag{1}$$

where r denotes the packet loss ratio, and w is a weight that is set for specific type of sensor. Fig. 6 illustrates an example of QoHM for two types of sensor readings (ECG and SaO2), with respect to end-to-end packet loss. The reason that two different models are developed for different sensors is due to the fact that certain sensors may have higher priority and should tolerate less loss (for example ECG). By increasing w, this will lower the loss tolerance of the sensor readings. In the example of Fig. 6, the QoHM models for ECG and SaO2 readings are allocated w of 4 and 2, respectively. The following Policy Extract presents an example of QoHM Policy for QoHM level 3 for one of the measurements (e.g. ECG or Sa02):

```
Policy Extract 2.

PR(5): Event 'QoHM_Value':
   IF ((QoHM is < 3)
     and (QoHM_Value from NurseDevice))
       {ReRoute(NurseTraffic);}
PR(6): Event 'QoHM_Value':
   IF ((QoHM is < 3)
     and (QoHM_Value from DoctorDevice))
       {ReRoute(DoctorTraffic);}
```

In the event that QoHM drops, a threshold maybe exceeded, which in turn could generate a ReRoute event for the *Data Reliability policy* (this is represented through PR(5), PR(6) in Policy Extract 2). The Data Reliability policy will as a result, invoke and change the configuration of cooperation between the sensors as well as routing of information, in order to improve the QoHM. Further details on the cooperation and data routing through the sensors will be provided in Section V. The following Policy Extract presents an example of policies for Data reliability:

```
Policy Extract 3.

PR(7): Event 'ReRoute':
   IF ((ReRoute.Target is Nurse)
     and (Reliability is Standard))
       {StepReliability(Nurse, Up);}
PR(8): Event 'ReRoute':
```

```
  IF ((ReRoute.Target is Doctor)
     and (Reliability is not MAX))
            {StepReliability(Doctor, Up);}
PR(9): Event 'ReRoute':
  IF ((ReRoute.Target is Doctor)
     and (Reliability.Doctor is Max)
     and (Reliability.Nurse is High))
        {ReduceTraffic();}
```

Three reliability levels are used; Standard, High and Maximum (Max). The PR(7) checks to see if the nurse's reliability setting needs to be increased from Standard to High, after detecting the 'ReRoute' event. In PR(8), if the doctors reliability is not Max and true, an increase in the reliability setting is performed. Rule PR(9) checks if both nurse's and doctors reliability settings are at their highest (which is High for Nurse and Max for Doctor), and if this is true, a 'ReduceTraffic' event will be invoked. This event will start to reduce traffic on different streams with a goal of ensuring that the highest priority information gets to the appropriate medical personnel. All 'ReduceTraffic' events are considered to possibly have the potential to be a system wide problem, and therefore are handled centrally by the GMS. GMS reduces the traffic based on the following ranking, where groups with no medical personnel will have their traffic reduced first, to minimize load on the network. In the event that the system continues to exhibit problems, then groups with only nurses will have their traffic reduced. However, if the problem persists then selected groups with both nurses and doctors will have their traffic reduced. Therefore, the traffic reduction has the following priority: (i) groups with no medical personnel involved, (ii) groups with nurses, or (iii) groups with nurses and doctors. The use of policies integrated with low level control addresses Challenge (ii) of the introduction, namely; the ability of medical officers to set requirements.

The application of policy based management in our solution provides essential high level domain specific access to practitioners for decision making. However, the intention is not to extend the state of the art in policy based management but more to integrate it and make use of it. Policy based management is a well researched domain and numerous research work have investigated Policy Conflict Analysis [14], [15].

The policy conflict analysis envisaged for our solution would be based on what is proposed in [14], where an initial analysis of a policy is performed before deployment, comparing it with already deployed policies. Therefore, conflicts are identified prior to deployment to ensure that the system remains in a stable state during operation.

V. Wireless transmission technology

While the previous sections described the policy based management system of our proposed architecture, this section will present the adaptability mechanisms of the underlying wireless sensor networks that can cater and support changes from the high level policies. Due to the low cost and energy efficiency requirements, we select IEEE 802.15.4 [16] as the underlying communication technology. Therefore, all sensors (including the WBAN sensors) are single half-duplex transceiver devices and can be tuned to multiple channels at the MAC layer. Communication between members of the groups is through the sensor networks and supported by the MAC and Network layer technologies presented in this section.

A. CAM-MAC-ARCB

Single MAC layer channel usage of IEEE 802.15.4 design significantly limits the capacity of the system due to performance degradation in case of large patient numbers coupled with the group communication. Therefore, considering the implementation costs we have selected single transceiver multi-channel protocols to be used at the MAC layer. Due to high risks of multi-channel collisions, these protocols are required to exhibit a high degree of cooperation. We have developed a cooperative negotiation protocol for multi-channel MAC known as CAM-MAC-ARCB, which extends from the original CAM-MAC protocol [17]. This section provides an overview of the cooperation process, where detailed description can be found in [17].

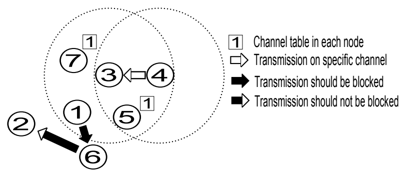

Fig. 7. CAM-MAC-ARCB negotiation process

An illustration of cooperation at the MAC layer is illustrated in Fig. 7. In the event that a sender (node 4) wishes to transmit a packet, a negotiation is initiated with the receiver (node 3) on the control channel. The negotiation will include information on the candidate data channel that the sender wishes to use. This negotiation process will be overheard by all the neighbours (nodes 1, 5, and 7), and if the sender and receiver agree on this channel, this information will be stored by all neighbouring nodes. In the event that a new pair of nodes (nodes 2 and 6) decide to negotiate on this same data channel, the neighbours will all veto this negotiation, since it has already been taken by a previous pair of nodes within the vicinity. In the case of the original CAM-MAC protocol, node 1 will veto the negotiation of nodes 2 and 6, even though the nodes are out of range from nodes 3 and 4. However, CAM-MAC-ARCB avoids unnecessary vetoing process through a virtual topology inferencing process. This in turn leads to higher throughput between the sensor nodes. Full details of the virtual topology inferencing process can be found in [17].

B. Gradient based routing

Uneven distribution of patients, medical personnel and presence of additional monitoring devices (e.g. ZigBee cameras) lead to varying network loads within the environment. In such cases group message delivery through highly loaded network regions may lead to QoHM degradation. In order to avoid this we use gradient-based routing technique that avoids highly loaded regions (Fig. 8(b)). The importance of using load sensitive routing becomes higher when the number of patients increase, as patients may gather around certain

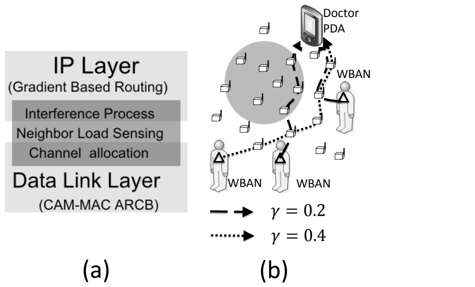

Fig. 8. Adaptive routing solution: (a) cross-layered integrated solution, (b) routing around high network load regions with different priority.

TABLE I
PATIENT WBAN PARAMETERS

WBAN SENSORS: 4 ECG Patches, 1 SaO2 Sensor, 1 Sink Measurement rates: ECG 200 bytes/s, SaO2 50 bytes/s
ZigBee Transceiver: CC 2420, Transmission rate 0.2 Mbps, Range: 7m, 1 Control Channel, 3 Data channels
Power consumption: Transmission (33mW), Reception (56.4mW) Idle (1.27mW), Sleep (0.06mW)
Infrastructure: 64 Environmental sensors in a grid topology 3 Doctors; 3 Nurses; 30 Patients; 4 Gateways Simulation time: 20 minutes; Averaged over 20 independent runs

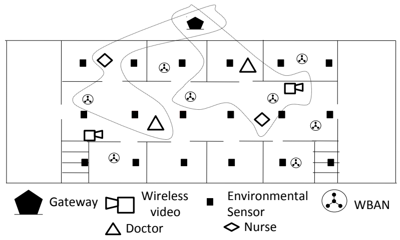

Fig. 9. Simulation scenario: hospital waiting area (50m X 50m) plan with WBAN equipped patients.

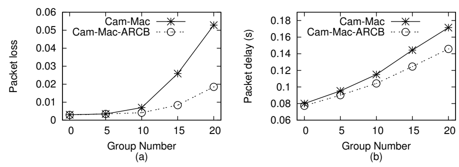

Fig. 10. Inter-group information exchange: (a) average packet loss ratio; (b) average message transmission delay.

locations leading to certain parts of the network being overloaded. Therefore, to improve communication reliability for inter-group communication, the solution uses a cross layered gradient-based routing technique built over the CAM-MAC-ARCB cooperation [17]. The technique stretches across Data Link and IP layers as presented in Fig. 8(a). The constant monitoring of ongoing negotiations at the MAC layer allows each network node to estimate its own link capacity and load. This estimation is further fed to the IP layer, where the routing process determines the path by creating a gradient field within the environment. Therefore, at each node i of the network the gradient field $G_{n,d,n\to i}$ represents its capacity for flow routing from node n to destination d and is represented through the following equation:

$$G_{n,d,n\to i} \quad = \quad \gamma \cdot \Phi_{i,d} + (1-\gamma) \cdot h_{i,d}, \tag{2}$$

where $h_{i,d}$ represents the normalized hop count from node i to destination d, and the $\Phi_{i,d}$ denotes the capacity of the node to route a flow. The routing process selects the path traversing through nodes with maximal gradient field values in order to increase chances of arriving at the destination. Therefore, $\gamma \cdot \Phi_{i,d}$ is a linear load based correction of the shortest path, where parameter γ represents reliability of the established routes and determines how far routes may divert from the shortest path while avoiding highly loaded regions of the network. The strength of this multi-hop routing approach for our monitoring solution, is that different paths can be taken for different types of data. For example, inter-group communication can be performed through longer routes, while WBAN data could be transmitted through shorter routes. The selection and strategy to increase γ is governed by the QoHM policy, where each γ corresponds to the reliability levels. The ability of sensor devices for load-sensing through constant monitoring of MAC layer negotiations together with the gradient-based routing address Challenge (iii) of the introduction.

VI. SIMULATION

In order to validate the proposed solution, simulation work has been conducted on our Java based event driven simulator. The simulation is divided into two sub-sections, where section VI-A evaluates the wireless sensor cooperation with respect to inter-group communication, and its influence on the quality of monitoring data, while section VI-B evaluates the dynamic policy operation based on changes in QoHM, and its impact on wireless sensor cooperation.

A. Inter-group communication

In order to evaluate cooperation efficiency at the MAC layer, this section compares performance of the CAM-MAC-ARCB and CAM-MAC [17], with respect to varying group sizes and inter-group communications. More general evaluation of the CAM-MAC-ARCB protocol can be found in our earlier research work [17]. The simulation scenario represents a hospital waiting area (Fig. 9 and Table I for simulation parameters). Each patient is equipped with a WBAN, where the patient condition information is aggregated by the WBAN sinks and periodically reported to a doctor, nurse, and MDRS server via any of the gateways. The patient sensor readings are delivered via environmental sensors or sinks of other WBANs. During the simulation the number of patients with deteriorating conditions will slowly increase, resulting in increasing number of virtual groups formed.

Fig. 10(a) and (b) present scalability evaluation of the proposed system (Challenge (iii)) and show results of "Packet

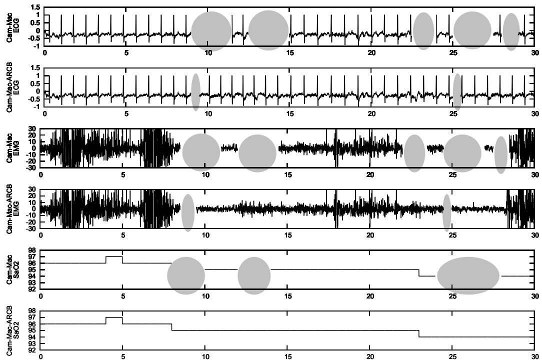

Fig. 11. Comparison of CAM-MAC-ARCB and CAM-MAC for WBAN sensor readings of ECG, EMG, SaO2 for a specific patient.

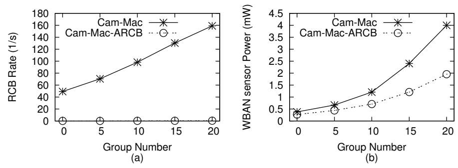

Fig. 12. Comparison of CAM-MAC and CAM-MAC-ARCG: (a) average redundant channel blocking; (b) average power consumption for a WBAN sensor node.

Loss" and "Packet Delay" as the number of virtual groups increase. The increase in the number of virtual groups will result in increased data sent to the doctors and nurses, which in turn maps to overall system load increase.

Although both protocols demonstrate good cooperation performance, CAM-MAC-ARCB clearly outperforms CAM-MAC. Fig. 11 illustrates ability of the proposed system to extract information from WBAN (Challenge (i)) and presents the impact of packet loss on the sensor data for both protocols (the sensor readings are real data obtained from patient monitoring [18]). The grey circles represent the loss in data during the transmission. The impact is amplified by star topology of individual WBAN systems. Therefore, Redundant Channel Blocking (RCB) behaviour at the WBAN sink affects collecting measurements from all the sensors leading to close in time losses of different measurements.

The performance improvement of CAM-MAC-ARCB over CAM-MAC protocol is attributed to the ability of CAM-MAC-ARCB sensors to learn and infer from the negotiation process of their neighbors. This in turn minimizes the amount of RCB performed by the nodes, which in turn reduces the waiting time prior to packet transmission. Fig. 12(a) presents results for RCB rate of the two protocols. Since CAM-MAC has to spend more time on a packet transmission during the waiting period, this also leads to higher power consumption of WBAN sensors compared to CAM-MAC-ARCB (Fig. 12(b)). Due to low mobility of the patients and sequential appearances of new patients in our scenario, the technique nearly eliminates cases that can lead to RCB.

In order to evaluate the cross-layered gradient based routing

TABLE II

SIMULATION PARAMETERS

Standard reliability γ:	0.0	Standard reliability γ:	0.2
Max reliability γ:	0.4	No. of cameras:	4
Camera transmission rate:	35 Kbps		

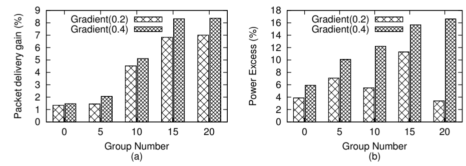

Fig. 13. Comparison of Gradient Based Routing for High and Max reliability in relation to Standard reliability: (a) packet delivery gain (b) WBAN sensor power consumption excess.

TABLE III

SIMULATION EVENT SEQUENCE

Interval	New groups formed	Time	Action
440s-800s	10	1200s	PR(7)
1600s-2000s	4	2400s	PR(8)
2800s-3200s	2	3600s	PR(9)

with respect to varying virtual groups, we analyzed High and Max reliability values in comparison to Standard reliability (see Table II for γ values corresponding to each class). The evaluation exploits the simulation scenario described above with an addition of 4 ZigBee wireless cameras used for patient monitoring.

Fig. 13(a) shows packet delivery improvement over standard routing protocol for the routing of High and Max reliability values. In our evaluation, the standard routing protocol is the AODV protocol. Exploiting Max reliability increases the capacity of the newly established patient-nurse and patient-doctor communication routes to traverse away from highly loaded areas. As we have discussed earlier, increasing route reliability increases network load created by the existing data flows, which also results in WBAN sensor power consumption increase. Fig. 13(b) represents relative power consumption increase with respect to the two reliability values in comparison to Standard reliability. In the case of 20 Groups being formed during the simulation, using gradient-based routing of Max reliability value improved packet delivery ratio by 8% and caused 16% power consumption increase in comparison to Standard reliability.

B. Dynamic policy operation evaluation

The final simulation section evaluates the operation of the overall architecture, where ability of the system to satisfy the set of requirements provided by medical personnel is investigated (Challenge (ii)). The simulation setup is similar to Section IV-A with 4 additional ZigBee cameras. Initially all 30 patients are stable, where deterioration of patients condition will slowly occur at 3 specific time intervals, leading to formation of the virtual groups. Group formation and additional patient-nurse and patient-doctor communication will result in overall network load increase, which in turn affects the QoHM. In order to address this problem, the scenario will take three actions including two traffic re-routing PR(7) and PR(8) policy rules of Section IV-C and one traffic reduction PR(9). In order to improve energy efficiency of the system and prolong its energy lifetime, all the communication routes are established with a Standard reliability parameter value. Intervals of new group formation and times of policy rules invoking are presented in Table III. The PR(9) traffic reduction mechanism turns off 2 out of 4 ECG patches for each stable patient.

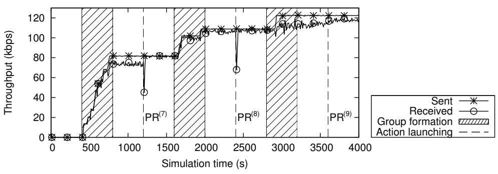

Fig. 14. Dynamic policy adaptation: patient to nurse throughput performance.

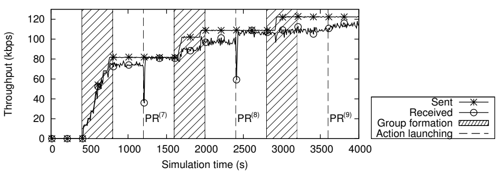

Fig. 15. Dynamic policy adaptation: patient to doctors throughput performance.

Fig. 14 and 15 presents the throughput performance between patient-nurse and patient-doctor with respect to time. The figures also show the point when groups are formed, and times when policy action are taken. As shown in both figures, as actions are taken, the performance of received packets gets closer to the sent packets. Launching PR(7) and PR(8) involves updating local gradient fields to re-route on-going data flows, which leads to a short performance disruption. However, the short duration of the disruption makes it negligible from the perception of medical staff.

Fig. 16 (a) and (b) present the delivery ratio and QoHM for one of the critical patients from the point of view of a doctor. In this scenario we have set the QoHM threshold of PR(5) and PR(6) at 4.5. Therefore, once QoHM drops below this threshold, the policies will get invoked, which will invoke policy rules PR(7) and PR(8). For both ECG and SaO2 readings, Fig. 17 (a) and (b) present the average and the range of QoHM values, where the averaging is performed across doctors monitoring critical patients. The QoHM is based on the weight values of Fig. 6 for both ECG readings (weight 4), and SaO2 (weight 2). The exponential nature of QoHM values intensifies the impact of additional group communication routing through network sections of high load. However, the impact is local and does not affect the entire network, which is confirmed by the variability of QoHM

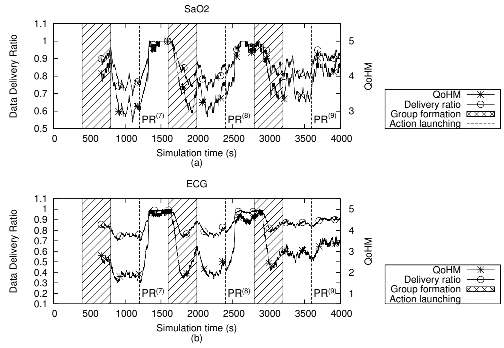

Fig. 16. ECG and SaO2 reading of a critical patient delivered to a doctor: QoHM and data delivery ratio evolution.

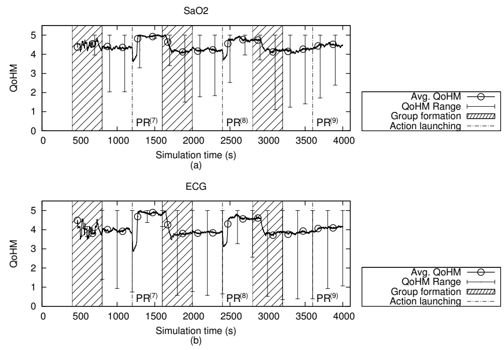

Fig. 17. Aggregated QoHM evolution for ECG and SaO2 reading of critical patients delivered to medical doctors.

values presented on the figure. This impact is encountered due to the launch of PR(7) - (9) by the affected groups.

VII. Conclusion

Wireless Body Area Networks (WBAN) provides a new opportunity for monitoring healthcare patients. In this paper we propose the Virtual Group Enabler architecture for virtual group formation that allows medical personnel to continuously analyze patient monitoring, and fine tune changes in sensor behavior through high level polices. The dynamic policy changes performed by the medical officers can improve the sensor readings of critical patients when performance of the network degrades. We have also proposed a new metric called QoHM, that allows medical officers to provide feedback on the quality of sensor readings by setting their preference through policies. The hierarchical policy structure can allow doctors to specify their QoHM threshold, which in turn will go down and configure the cooperation and routing behavior of the sensor nodes. The proposed solution is evaluated through simulation using our custom made Java event-based simulator.

Acknowledgment

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Appendix E:

"Joint throughput and packet loss probability analysis of IEEE 802.11 networks"

Joint throughput and packet loss probability analysis of IEEE 802.11 networks

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***Abstract*—Wireless networks have grown their popularity over the past number of years. Usually wireless networks operate according to IEEE 802.11, which specifies protocols of physical and MAC layers. A number of different studies have been conducted on performance of IEEE 802.11 wireless networks. However, questions of QoS control in such networks have not received sufficient attention from the research community. This paper considers modeling of QoS of IEEE 802.11 networks defined in terms of throughput requirements and packet loss probability limitations. An influence of sizes of packets being transmitted through the network on the QoS is investigated. Extensive simulations confirm results obtained from the mathematical model.**

***Index Terms*—wireless, IEEE 802.11, QoS, throughput analysis, packet loss analysis, mathematical modeling**

I. Introduction

In the recent years a growth of popularity of wireless networks has been observed. Different studies propose using such networks to provide transmissions of data between users, audio and video conferences. Many of such applications are sensitive to quality of service (QoS) provided by the underlying network. However, a problem of providing service of guaranteed quality has not been solved yet for wireless networks. In this article QoS is considered in terms of probability for an average packet sent through the network to be delayed more then a certain predefined timeout. Later on this probability is called as "packet drop probability" as it's presumed that transmitting of all such packets is canceled by the upper layers. Also QoS is considered in terms of throughput. Thus, QoS is defined in this article as a set of requirements, where each node requests a connection capable of providing a certain predefined throughput, while the connection's packet drop probability doesn't exceed a certain threshold.

Typically wireless networks operate according to IEEE 802.11 standard [1], which specifies distributed coordinated function (DCF) for MAC layer channel allocation. DCF presents a random data channel access scheme based on carrier sensing. When a wireless node gets a packet to transmit through the wireless network it starts data channel carrier detection process. Once the node detects that the channel has been idle for distributed inter-frame space (DIFS), it initializes a random back-off interval and holds off the transmission for the interval, which length depends on the packet retransmission history. When the back-off interval expires the node (the sender) initiates a transmission. DCF protocol specifies RTS/CTS transmission scheme. The scheme implies a handshake technique, where the sender sends a "request to send" (RTS) packet and the receiver replies by sending a "clear to send" (CTS) packet. RTS and CTS packets include all necessary information, which describes the data packet transmission. CTS/RTS packets' exchange lets neighbors of the sender and the receiver know about the transmission; so they can successfully avoid colliding with it. Once the handshake is successfully accomplished the sender performs the data transmission, which is concluded by an acknowledgment phase. During the acknowledgment phase the receiver confirms if the transmission was successful. In case a packets delivery is not confirmed the sender schedules a re-transmission.

DCF mechanism reduces a number of collisions that a packet suffers in average. However, the process of MAC layer packet processing creates a certain time overhead, which is called in this article as "coordination overhead". This article concentrates on investigating of an influence of sizes of packets being transmitted through the network on coordination overhead, which in turn influences network performance both in terms of throughput and packet drop probability.

II. Related work

A number of different researches have been dedicated to studying performance of IEEE 802.11 MAC layer protocol. Bianchi's seminal paper [2] considers single-hop wireless networks operating under saturated conditions, when each station has a packet to transmit at any given time. For modeling purposes Bianchi uses collision decoupling approximation which assumes that each station in case of a transmission attempt suffers a collision with a fixed probability that doesn't depend on the collision history. Bianchi presents a Markov chain model that allows estimating network performance in terms of different metrics such as: throughput, average number of retransmissions, average packet MAC layer delay. Certain research papers aim to extend Bianchi's work to allow modeling more general cases. Thus [3], [4], [5], [6] concentrate on modeling networks working under non-saturated conditions. Issues of fairness are considered in [6], [7] and [8]. [9] and [10] provide extensions for IEEE 802.11e single-hop networks operating under saturated conditions. However, papers presented above mostly concentrate on throughput related issues while

IEEE Symposium on Computers and Communications, (Riccione, Italy), 2010

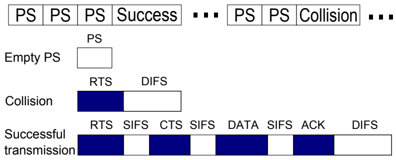

Fig. 1. Network operation time model

MAC layer packet delay related issues modeling is left behind. To the best of our knowledge only two approaches to analyze packet drop probability have been presented in the literature. Both approaches consider single-hop wireless networks operating under saturated conditions. Approach presented in [11] and [12] is based on the dividing of the network operating time into fragments of certain lengths representing different channel states such as: collision of two or more transmission attempts, successful transmission and empty physical layer slot. This approach is derived directly from Bianchi's model and is used for analytical analysis presented in this paper. The second approach is presented in [13] and [14].

III. Network operation time model

This paper considers single-hop wireless networks operating under saturated traffic and perfect channel conditions. This section presents a network operation time model, which is based on dividing the operation time into fragments of certain types. This approach is derived from [2]. In a wireless network operating under saturated conditions a station observing wireless channel can see the channel only in three possible states (Fig. 1): Empty PS, Collision, Successful transmission.

A wireless node observes the channel being at "Empty PS" state when the station is experiencing a back-off interval and none of its neighbors attempts to transmit. As nodes go through a back-off interval by sensing empty physical layer slots, the state's duration equals to the slot length and is referenced later on as D_{emPS}.

A wireless node observes the channel being at "Collision" state when two or more stations attempt transmitting data through the channel. According to DCF mechanism nodes transmit RTS packets providing information describing proposed data transmission. Those packets collide with each other, and that is observed by other nodes remaining silent at the time. After the collision all nodes start sensing DIFS (distributed inter-frame space) interval, which is also included into the state. Hence, "Collision" state's duration equals to a sum of lengths of RTS packet transmission and DIFS interval. The length of such state is referenced later on as D_{col}. Note that the node may be or may be not one of the nodes transmitting during the state.

A wireless node observes the channel being at "Successful transmission" state when only one node is attempting a transmission. In this case, the transmitting node and its receiver go safely through all necessary data packets' exchange and all their neighbors observe the packets' exchange process and remain silent during the process. After the successful data transmission all nodes start sensing DIFS interval, which is also included into the state. Hence, "Successful transmission" state duration equals to a sum of lengths of full DCF packet exchange procedure and DIFS interval. The length of such state is referenced later on as D_{suc}. Note that the node may be or may be not the one transmitting during the state.

Total network operating time may be presented as a construction of intervals of the three types, which are presented above (Fig. 1). Each of these intervals is referenced later as a virtual time slot. Type of a virtual slot depends on a number of wireless nodes attempting transmissions during the slot. Each node attempts a transmission during a virtual slot according to DCF mechanism. Bianchi's model provides a probability τ that a station attempts a transmission during a generic virtual time slot. This probability can be found as a solution of the following system of nonlinear equations:

$$\begin{cases} p & = & 1-(1-\tau)^{n-1} \\ \tau & = & \frac{2}{1+W+p\cdot W\cdot\sum_{i=0}^{W-1}2p^i} \end{cases}$$

where n donates a number of wireless stations of the wireless network, W donates initial back off window size, p donates probability that a station meets with a collision during a transmission attempt. Variable m describes maximum back off window size extension due to collision suffering. Variables W and m are DCF parameters and their use and full description can be found in [1].

Knowing τ probability allows calculating a probability that a generic slot is of a certain type. Following formulas give probabilities P_{emPS}, P_{col} that a generic virtual time slot is of "Empty PS" and "Collision" types. Probabilities P_{sSuc} and P_{oSuc} donate probabilities that the a generic virtual time slot includes a successful data transmission made by the observing node and one of its neighbors correspondingly.

$$\begin{array}{lcl} P_{emPS} & = & (1-\tau)^n \\ P_{col} & = & 1-(1-\tau)^n - n\cdot\tau\cdot(1-\tau)^{n-1} \\ P_{sSuc} & = & \tau\cdot(1-\tau)^{n-1} \\ P_{oSuc} & = & (n-1)\cdot\tau\cdot(1-\tau)^{n-1} \end{array}$$

Therefor MAC layer operation time can be presented as a sequence of independent random values $\{X_i\}$ representing virtual time slots. All random values are distributed identically with discrete probabilities P_{emPs}, P_{col}, P_{sSuc} and P_{oSuc} corresponding to D_{emPS}, D_{col}, D_{suc} and D_{suc} value correspondingly.

IV. QoS Analysis

This section studies an influence of the size of packets transmitted through the network on QoS and provides an analytical analysis based on the time model presented in the previous section.

A. Throughput analysis

Aggregate throughput of a single hop wireless network has been previously considered in a number of different studies. Usual aggregate throughput estimation uses an approach similar to the one described in Section III. Aggregated throughput

S is evaluated as a division of virtual time slot payload expectation by virtual time slot length expectation.

$$S = \frac{E\left[Payload\right]}{E\left[Slot\_Duration\right]} \tag{1}$$

Since payload of any virtual time slot, which is not of "Successful Transmission" type, is zero, and any successful transmission slots has $Size$ (packet size) as its payload then:

$$E\left[Payload\right] = (P_{sSuc} + P_{oSuc}) \cdot Size \tag{2}$$

$$\begin{aligned} E\left[Slot\_Duration\right] = & \ D_{suc} \cdot (P_{sSuc} + P_{oSuc}) \\ & + D_{col} \cdot P_{col} \\ & + D_{emPS} \cdot P_{emPS} \end{aligned} \tag{3}$$

Considering D_{suc} as a linear function gives:

$$D_{suc}(Size) = \frac{Size}{TR} + Slip \tag{4}$$

where $Slip$ denotes duration of DCF packet exchange, which has to be done in order to establish a transmission, TR donates transmission rate. Then equation 1 considering 2, 3 and 4 can be presented in the following form

$$S(size) = \frac{A \cdot size}{B + D_{suc}(size) \cdot A} \tag{5}$$

where A and B values don't depend on the packet size and can be calculated using equations 1, 2, 3 and 4. Provided that A, B and $Slip$ are all positive values; it's easy to show that equation 5 is a monotonically increasing function of $Size$. This meets general sense considering of DCF function, as in case of the same coordination mechanism transmitting bigger packets would reduce percentage of time spent on coordination. This effect has already been mentioned in a couple research papers (see [2]), but to the best of our knowledge no analytical explanation to the monotony of the growth has been given before. Thus, in terms of aggregate throughput it is beneficial for network nodes to use bigger packets for transmitting.

B. Packet drop probability analysis

Using the operation time model described in Section III, coordination overhead can be presented as a sum of virtual time slot durations corresponding to random values X_i, which appear in the sequence before the first arrival of X_k value representing a successful transmission of the observing node. Such sum is also can be naturally presented as a Random Walk process, where a particle walks a half-line in one direction until a certain event happens. Thus, the particle makes steps in the same direction of sizes D_{emPS}, D_{col}, D_{suc} and 0 with probabilities P_{emPS}, P_{col}, P_{oSuc}, P_{sSuc}. Successful transmission of the observing node is presented by the last 0 step, which doesn't contribute to the cooperation overhead. Once the particle makes 0 step it stops walking and remains at the position it has got to. Distribution of distances, that the particle may walk, models DCF coordination overhead distribution. In this article such distributions are obtained from Random Walk simulations.

Random Walk presentation helps understanding packet size influence on the cooperation overhead. As the Random Walk

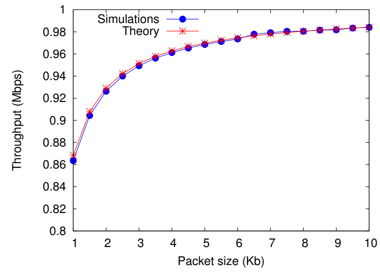

Fig. 2. Throughput analysis: 20 nodes, 1 Mbps rate, initial back-off windows equals 32, maximum back-off extension equals 5

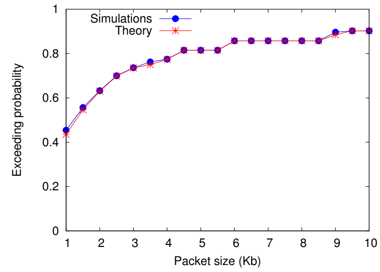

Fig. 3. Cooperation overhead analysis: 20 nodes, 1 Mbps rate, initial back-off windows equals 32, maximum back-off extension equals 5, 0.15s coordination delay

steps are discrete independent random variables, the walking distance is also a discrete random variable. Each distance T the process may walk is a finite sum: $\sum_{i=1}^{n} X_i$, and the same distance may be covered by a number of different combinations of steps. Those combinations define probability that the process walks the distance. Increasing size of transmitted packets only increases D_{suc} value, and leaves other parameters the same. This leads to the situation when a combination which corresponded to distance T will correspond to some other distance $T^{'} \geq T$. This will stretch random walk distance (cooperation overhead) distribution along the time axis, which in turn leads to a packet drop probability increase.

V. Simulations

Simulations are conducted for wireless networks 20 nodes. Each network node is equipped with a single IEEE 802.11 transceiver, which is capable of transmitting at 1 Mbps rate. All nodes work at MAC layer according to DCF function, which has its initial back-off window of size 32, and the window is allowed to be extended not more then 5 times. All nodes operate under saturated conditions. Packets, which cooperation overhead values exceeds 0.15s, are considered to be dropped by one of the upper layers. All results are averaged over 10 simulation runs. Figures 2 and 3 present good agreement between theoretical and simulation results. Figures also show growth of throughput and packet drop probability with packet size increasing. This agrees with the conclusions of previous sections.

VI. Conclusion

QoS defined in terms of throughput requirements and packet drop probability has been analyzed. The study shows that despite throughput growth, increasing size of packets sent through the network may lead to QoS degradation in terms of packet drop probability. Thus, the study suggests a trade-off between throughput increasing and packet drop probability degradation to be considered in order to achieve the best performance.

VII. Acknowledgments

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Appendix F:

"On Delay Distribution in IEEE 802.11 Wireless Networks"

On Delay Distribution in IEEE 802.11 Wireless Networks

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***Abstract*—IEEE 802.11 wireless networks have received much attention over the past number of years. Still certain aspects of behavior of wireless networks have not been studied well enough. For example, understanding MAC layer packet delay distribution remains challenging yet. However, obtaining such distribution is highly beneficial for modeling QoS provided by wireless networks. This paper proposes a way of obtaining MAC delay distribution in case of single-hop networks. The proposed way is based on theory of terminating renewal processes and delivers approximation of good precision.**

***Index Terms*—IEEE 802.11, MAC layer, modeling, delay distribution**

I. Introduction

For the past number of years wireless networks have grown their popularity. Different services are delivered to the end users by using such networks. These services include audio and video conferences, instant messaging and gaming. Certain of the services mentioned above are quite sensitive to quality of service (QoS) provided by the underlaying wireless network. QoS may be defined in a number of different ways depending on requirements of the upper layer (network layer and above) services being delivered over the network. Quite often QoS demands a restriction of probability for a packet sent through the media to be delayed more then a certain predefined packet delivery timeout, as once the timeout expires the packet's delivery is canceled by one of the upper layers. This probability is called as *packet drop* probability. For each packet it's overall delay is a convolution of delays gained by the packet at different layers. This paper aims at modeling packet delay gained at MAC layer. Typically wireless networks at MAC layer operate in accordance to DCF mechanism of IEEE 802.11 standard [1]. DCF mechanism specifies RTS-CTS-DATA-ACK sender-receiver handshake that establishes a transmission and also informs neighboring nodes. This allows reducing a number of data transmission collisions and improves wireless network performance. However, MAC layer packet processing causes certain delays, which are considered in this article.

II. Related Work

Markov chain probability model describing behavior of a generic node of a homogeneous single-hop wireless networks operating under saturated conditions was proposed by Bianchi [2]. The model made possible estimating network performance in terms of throughput, average delay, average packet retransmission number and some other metrics. A number of extensions of the model for unsaturated traffic conditions were proposed by the research community. For example Ergen and Varaya [5] presented a model simulating behavior of network nodes transmitting at different rates. Zheng et al. [11] and Lu et al. [11] proposes models predicting nodes' behavior in imperfect channel conditions. All Bianchi's model extensions mentioned above fail on simulating IEEE 802.11 post back-off period. In non-saturated traffic conditions a node enters this period in case it has completed its own transmission and has no more packets to be sent over the network. Cantieni et al. [4] and Malone et al. [12] in their works considered IEEE 802.11 post back-off period as well. In addition several studies considered deeper modeling of different aspects of performance of IEEE 802.11 networks operating under saturated conditions. Thus, Taher et al. [6] and Hui and Devtsikiotis [7] proposed enhancements simulating behavior of IEEE 802.11e networks. Approaches different to Markov chain modeling can be found in [9], [10] and [8].

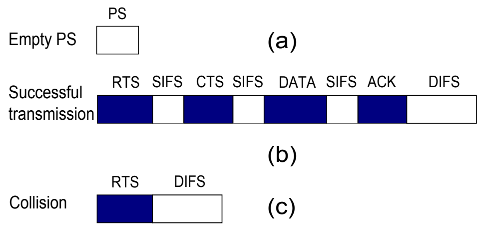

Fig. 1. Time intervals

Mostly all existing models target issues of throughput and fairness, while delay related issues remain obscure. Almost all presented above papers provide estimations of average MAC layer packet delay, while estimating delay variance and distribution is left behind. However, a delay jitter estimation was presented by Xie et al. [10] and by Qi et al. [12]. Yet obtaining packet delay distribution remains unsolved.

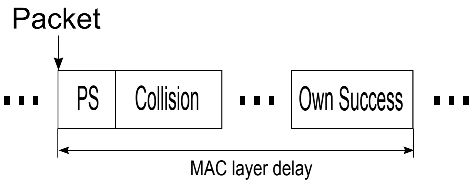

Fig. 2. Time sequence

III. MAC LAYER DELAY AS A TERMINATING RENEWAL PROCESS

This study suggests a model using time fragmentation, where the total time is presented as a sequence of intervals of Empty, Success and Collision types (Fig. 1, 2) corresponding to none, single and two or more simultaneous transmission attempts. D_{emp}, D_{suc}, D_{col} denote Empty, Success and Collision interval length. The proposed model is built for a generic wireless station trying to transmit a packet (mentioned below as *the transmitter*). The proposed model is built on top of a behavior model describing a generic wireless node (Section II for examples). For each interval the behavior model should supply τ_{tr} probability of the transmitter attempting a transmission, τ_{nb} probability of one of the transmitter's neighbors attempting a transmission. This, allows calculating probabilities of the following events: no transmission attempts (P_{emp}), two or more transmission attempts (P_{col}), the senders' successful transmission (P_{own}), a neighbor's successful transmission (P_{suc}).

$$\begin{aligned} P_{emp} &= (1-\tau_{tr})\cdot(1-\tau_{nb})^{n-1} \\ P_{suc} &= (n-1)\cdot\tau_{nb}\cdot(1-\tau_{tr})\cdot(1-\tau_{nb})^{n-2} \\ P_{own} &= \tau_{tr}\cdot(1-\tau_{nb})^{n-1} \\ P_{col} &= 1-P_{emp}-P_{suc}-P_{own} \end{aligned}$$

Overall delay obtained by a packet can be presented as a sum of the following: delay obtained on the upper network layers (above MAC), MAC layer delay. This article focuses at MAC layer delay. It is assumed that packets are not passed to MAC layer by the upper layers till the moment when the media has been confirmed free. Thus, the MAC layer delay can be presented as a terminating renewal process, which terminates with P_{own} probability and can be presented as a sequence of S_n such as:

$$S_n = T_1 + T_2 + \ldots + T_n + D_{suc}, \tag{1}$$

where all T_i are independent and have the same improper probability density function f and probability distribution function F:

$$\begin{aligned} f(D_{emp}) &= P_{emp} \\ f(D_{suc}) &= P_{suc} \\ f(D_{col}) &= P_{col} \\ F(\infty) &= 1-P_{own} \end{aligned}$$

From the renewal process theory (see [3]) it's known that if for some value χ:

$$\int_0^\infty e^{\chi\cdot y}F\{dy\} = 1 \tag{2}$$

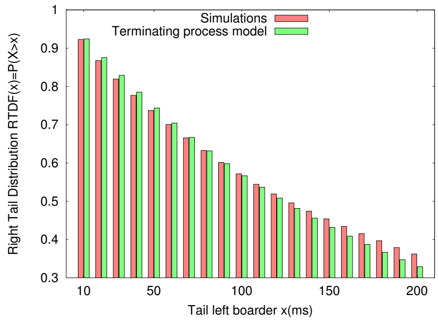

Fig. 3. Model evaluation packet delay right tail distribution. 20 Nodes

then for time M of the process termination:

$$P\{M>t\} \approx \frac{1-F(\infty)}{\chi\cdot\mu}\cdot e^{-\chi\cdot t}, \tag{3}$$

where

$$\mu = \int_0^\infty y\cdot e^{\chi\cdot y}F\{dy\} \tag{4}$$

Since T_i are discrete random variables then eq. 2 and 4 can be presented in the following way:

$$\begin{aligned} 1 &= P_{emp}\cdot e^{\chi\cdot D_{emp}} + P_{col}\cdot e^{\chi\cdot D_{col}} \\ &\quad + P_{suc}\cdot e^{\chi\cdot D_{suc}} \end{aligned} \tag{5}$$

$$\begin{aligned} \mu &= D_{emp}\cdot P_{emp}\cdot e^{\chi\cdot D_{emp}} \\ &\quad + D_{col}\cdot P_{col}\cdot e^{\chi\cdot D_{col}} \\ &\quad + D_{suc}\cdot P_{suc}\cdot e^{\chi\cdot D_{suc}} \end{aligned} \tag{6}$$

Solving eq. 5 gives χ value. Knowing χ allows obtaining μ value from eq. 6. Finally, knowing values χ and μ allows approximating probability $P\{M>t\}$ from eq. 3. This in turn allows estimating MAC layer delay d distribution, as:

$$P\{d\in[a;b]\} = P\{M>a\} - P\{M>b\} \tag{7}$$

$$P\{d\in[0;c]\} = 1 - P\{M>c\} \tag{8}$$

Formulas given in eq. 7 and 8 provide approximation of MAC layer delay distribution as a histogram. As the formulas are based on eq. 3, which is an approximation for probability $P\{M>t\}$ as t approaches infinity. However, as normally D_{emps} and D_{col} are minor in comparison to D_{suc} in conjunction with relevantly high probabilities P_{emps} and P_{col} in cases of high load presented formulas are expected to provide approximation of good precision.

IV. SIMULATION

While the previous sections concentrate on describing modeling aspects of MAC layer delay distribution, this section compares results gained from the terminating process model against results achieved from Java based simulations. Simulations have been conducted in order to validate proposed mathematical model and delay distribution approximation. Results for single-hop wireless networks of 20 and 30 nodes

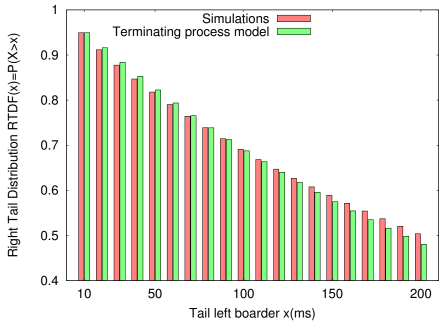

Fig. 4. Model evaluation packet delay right tail distribution. 30 Nodes

TABLE I
PARAMETER VALUES FOR MODEL AND SIMULATIONS

SIFS	28 us	DIFS	128 us
Physical slot	50 us	RTS	350 us
CTS	350 us	ACK	300 us
Data Packet	8200 us	Nodes	20

TABLE II
PACKET DELAYED MORE THEN 200 MS PROBABILITY

	Terminating process model	Simulations
20 Nodes	0.329	0.362192
30 Nodes	0.4803	0.503763

operating under saturated traffic conditions are presented in this section. Bianchi model [2] is chosen as the wireless node behavior model. Thereby transmission probabilities τ_{tr} and τ_{nb} both are suggested to be of τ value, where τ is a solution of the following system of equations:

$$\begin{cases} p &= 1-(1-\tau)^{n-1} \\ \tau &= \frac{2}{1+W+p\cdot W\cdot\sum_{i=0}^{m-1}2p^i} \end{cases}$$

In the equation τ and p are desired quantities. τ donates the probability of a generic node to be transmitting in a generic time slot; p donates a conditional probability that a node meets with a collision in case the node is transmitting during a generic time slot; n donates number of wireless nodes of the network; W donates initial contention window size; m donates maximum number of back-off window size increases that a node can have.

Each Java simulation run models 20 minutes of work of a real wireless network and all results are averaged over 20 runs. During each simulation nodes transmit packets of 1kb through 1Mbps wireless channel. All nodes operate according to DCF function. Durations of packet transmissions, DIFS and SIFS intervals, and physical layer slot duration are presented in Table I.

Fig. 3 and 4 present results for Packet Delay Right Tail Distribution function (RTDF, where $RTDF(x) = P(X > x)\ for\ x \in \Re$ probability that packet delay exceeds x). Presented results show good agreement between mathematical model and simulation. In addition to the figures Table II gives values of RTDF(200 ms) obtained from the model and simulation. As the presented results show approximation error growth with increase of delay value. However, the error of approximation does not exceed values 0.0332 for networks of 20 nodes and 0.0235 for networks of 30 nodes. Therefore the model provides prediction of good quality as expected.

V. CONCLUSIONS

Obtaining MAC layer packet delay distribution is quite important for analyzing performance of IEEE 802.11 networks. This paper provides a way of estimating MAC layer packet delay distribution for the case of single-hop wireless networks. The way uses a terminating renewal process for modeling MAC layer delay. The proposed solution is based on eq. 3, which is an approximation as t approaches infinity for a probability that the process terminates after a time point t ($P\{M > t\}$). The proposed way delivers approximation of good quality.

ACKNOWLEDGMENT

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Appendix G:

"Joint Delay and Energy Model for IEEE 802.11 Networks"

Joint delay and energy model for IEEE 802.11 networks

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Abstract Popularity of IEEE 802.11 networks has increased dramatically over the past number of years. Nowadays audio/video conferencing, gaming and other Quality of Service (QoS) sensitive services are being delivered to the end users over wireless. Commonly probability for a packet to overstay a specific timeout serves as a QoS metric, and obtaining MAC layer packet delay distribution is highly important for this QoS prediction. Usually wireless devices are equipped with energy supplies of limited capacity, and accurate estimation of their energy expenditure is essential from the network design point of view. Meanwhile, as packets of longer delay normally have higher energy transmission cost, there is a certain dependency between the two metrics. This paper considers internal structure of the metrics and proposes a mathematical model that allows obtaining their individual distributions together with the joint distribution. The model presents a random sum, where the summand formation is determined by a Terminating Markov Process. The model has been validated through comparison with results of NS3 simulation.

Keywords IEEE 802.11 · packet delay · energy consumption · modeling · joint distribution

Mathematics Subject Classification (2000) MSC 68Q87 · MSC 68W20 · MSC 68W40

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1 Introduction

Due to the convenience of connectivity, coupled with the popularity of the Internet, the use of wireless networks have grown exponentially in recent years. Audio and video conferencing, instant messaging and on-line gaming could serve as typical examples of applications benefiting from the use of wireless networks. A substantial number of these applications are rather sensitive to the provided Quality of Service (QoS). Quite often QoS requirements formulate restrictions to the overall packet delay, where a certain percentage of the packets is expected to be delivered within a predefined timeout. Packets that have exceeded their timeouts are normally dropped by their applications as containing outdated data. Although research in wireless networks have received tremendous attention in recent years, estimating such a percentage remains challenging.

Due to the broadcast nature simultaneous wireless transmissions are subject to mutual interference which may lead to their collision and failure. Therefore, such transmissions of nodes located within a certain vicinity of each other require additional synchronization and scheduling that is performed at the Media Access Control (MAC) sub-layer of the Data Link layer. Typically a wireless network operates at the MAC layer in accordance to CSMA/CA mechanism specified by the IEEE 802.11 standard [1]. The mechanism improves performance of the network by reducing the amount of collisions and re-transmissions suffered by its packets. However, the mechanism also presents a source of additional stochastic delay for transmissions of these packets. Therefore, estimating MAC layer delay distribution provides essential information for the overall delay estimation that in turn is required for QoS prediction.

Submitted: currently under review, 2012

Ability to predict QoS for a given wireless network is highly beneficial from the engineering perspective.

At the same time wireless devices are commonly equipped with energy supplies of limited capacity, and with the new “green agenda”, optimization of their energy consumption is essential. For that purpose nodes are enabled to switch to a specialized sleep mode of considerably low energy consumption. However, a good quantity of energy expenditure results from the use of the CSMA/CA mechanism, where this energy cost is higher for packets that have longer transmission time since the mechanism requires the node to remain awake and exchange data with its neighbors for a longer period of time. Therefore, there is a certain dependency between packet delay and packet transmission energy. Hence, as lowering packet transmission timeout reduces time spent by packets at the MAC layer, it sacrifices QoS while improving overall energy consumption. Similar trade-off was previously described by Chen et al. [2]. Having knowledge of this dependency can in turn enable us to determine a packet delivery timeout that provides services with a satisfactory delivery ratio together with an optimized energy consumption. To date, only a limited number of papers regarding MAC layer packet delay distribution for IEEE 802.11 networks exist, while its relation to packet transmission energy has not been considered previously. The aim of this paper is to propose a mathematical model that estimates distributions for both packet transmission energy and delay, as well as their joint distribution. The model has also been validated through simulation work focusing on IEEE 802.11b technology.

The remainder of the paper is organized in the following order: Section 2 presents existing models, Section 3 presents overall network operation time as an event sequence, Section 4 proposes a random sum model for the analyzed delay and transmission energy metrics, Section 5 presents numerical computation of the model, Section 6 presents model evaluation and finally Section 7 concludes this article.

2 Related work

A number of different research studies have been dedicated to modeling behavior of IEEE 802.11 networks. This section gives an overview of the field and presents mathematical models proposed earlier.

Majority of the papers dedicated to modeling of IEEE 802.11 networks are based on a Markov chain model proposed by Bianchi [3]. The model considers wireless single-hop networks operating under saturated conditions. It describes behavior of a generic wireless network node and is built exploiting a collision decoupling assumption, which presumes that a packet being transmitted through the network meets a collision with a certain probability that does not depend on the packet’s collision history. The model provides a performance estimation in terms of throughput, average delay, average packet retransmission number and some other metrics for a homogeneous single-hop wireless network operating under saturated conditions. The model has had a tremendous impact on IEEE 802.11 network behavior modeling, and a number of enhancements of the original model has been proposed over the year. Thus Ergen and Varaiya [4] considered cases of network nodes transmitting at different rates. Networks operating in imperfect channels conditions were considered by Zheng et al. [5] and Lu et al. [6]. A number of studies were dedicated to particular protocols of the IEEE 802.11 family, for example, Hui and Devtsikiotis [7], Taher et al. [8], Tinerello and Bianchi [9] concentrated on modeling IEEE 802.11e networks. An extension of the model considering networks operating under non-saturated conditions was presented by Qi et al. [10]. Modeling such networks requires introducing additional so-called post back-off states, which a node enters once it has completed its own transmission and has no further packets. Such states were introduced by Qi et al. [10]. Various other enhancements of the original model were proposed. All presented above studies use packet buffer decoupling assumption, where it is presumed that for each node after the k^{th} successful transmission its packet buffer contains at least one packet with probability Q_k, which does not depend on the collision history of the k^{th} successful transmission. This assumptions allows obtaining quite accurate results in homogeneous case. However, it was shown by Huang and Duffy [11] that using packet buffer decoupling assumption leads to inaccurate results in case of heterogeneous networks modeling. Aspects of packet buffer modeling were also considered by Liu et al. [12]. Zhao et al.[13] addressed intra-flow packet contention in multi-hop networks, while the continuation of that work developed a comprehensive multi-hop model [14] that accounts for such factors as hidden node interference, capture effect, node density and traffic load of the network. Approaches different to Markov chain modeling were proposed by Tickoo and Sikdar [15] and by Xie et al. [16]. Kafetzakis et al. [17] proposed a model that allows each node of a wireless network to assess its effective bandwidth based on direct network measurements.

In spite of considerable amount of research devoted to the topic, majority of the papers focus on aspects related to network throughput and fairness, while delay modeling and estimation has not been adequately investigated. Yet, the problem has been addressed previously in certain studies. Thus, a previously mentioned work conducted by Qi [10] presents a delay jitter estimation. Delay mean (i.e. the first moment) and jitter (i.e. the second central moment) are commonly used for modeling performance of a wireless node as a M/G/1 queue, however Brandwajn and Begin [18] suggest that higher-order delay moments may have an impact on the modeling quality in certain cases. Ivanov et al. [19][20] presented an exponential estimation of packet service time distribution in case of a single-hop network operating under saturated traffic conditions. This paper extends that work by considering cases of non-saturated network loads and at the same time addressing issues of energy consumption.

3 Network operation time

This section presents network operational time as an event sequence, where this representation is a foundation of the further analysis. For the sake of brevity, this article only considers cases of homogeneous single-hop networks operating under various traffic load conditions. Each of the considered networks consists of a number of nodes uploading data via a gateway. The simplicity of the data exchange between of this particular scenario eliminates the necessity to incorporate a potentially complex packet exchange model into the proposed model. Therefore the analysis focuses directly on the performance of the CSMA/CA mechanism. Additionally despite the simplicity this traffic structure is rather realistic and appears in various sensor applications. The article assumes a simplified signal propagation model, where any two simultaneous transmissions result in a collision that affects their reception. Even though the propagation model provides a reasonable approximation, a more sophisticated may be required to capture various particularities of wireless transmissions (e.g. capture effect and hidden-node interference in multi-hop networks [13][14]). Nodes transmit packets of a fixed size, where packet arrival process at a node is Poisson. CSMA/CA mechanism describes autonomous scheduling of transmission attempts of wireless nodes gaining access to the media. The mechanism describes RTS/CTS and Basic access schemes. This paper considers only the Basic scheme. However, results could be enhanced to accommodate a more generic case. Thus, event sequence model built for the RTS/CTS scheme can be found in [19].

3.1 CSMA/CA mechanism

The Basic scheme describes a process of packet exchange between a sender and its receiver. The sender attempts transmitting data once it has gone through its back-off interval and senses that the channel has been idle for a DIFS interval. Success of the attempt is confirmed by the receiver through sending an acknowledgment packet. Absence of this acknowledgment is interpreted by the sender as a corruption of the transmission which results in its retransmission. Each two transmission attempts of the same node have to be separated by a back-off interval, whose length is determined by a back-off counter. When the node enters the back-off interval the counter is initialized with an integer value randomly chosen from $[0; 2^{k-1} \cdot W - 1]$ interval (*back-off window*), where W gives minimal back-off window size and k is a minimum between a constant m and a number of retransmissions of the currently transmitted packet. W and m are predefined by the standard. Back-Off counter identifies a number of non-used physical slots that the node has to skip before it attempts to transmit again. Once the transmission is accomplished and the node has no more packets to send over the network, it enters the back-off interval once again, and this is called the post back-off interval. Completing the post back-off process allows the node to skip the first back-off interval once the node receives a packet from the upper layers. Thus, the node initiates a handshake straight away after sensing the DIFS interval. All further transmission attempts have to be separated by back-off intervals. In case the node gets a packet to transmit during the post back-off, the interval becomes a regular back-off.

3.2 Operation time as a sequence of events

Careful consideration of the CSMA/CA mechanism allows representing its operation time from a point of view of one of the nodes (the target node) as a sequence of events of 5 types (Fig. 1) representing no transmission attempts (a), a successful transmission (b) and a collision (c) of one of the target node's neighbors, and finally a successful transmission (d) and a collision (e) of the target node itself. For each event its type depends on the number of simultaneous transmission attempts carried out by the network nodes. Each node during an event may be in any of the two states: *transmission attempt* and *hold off*. The *hold off* state represents back-off interval waiting and time when the node has no packets to send over the network. The *transmission attempt* state accounts for both attempts carried out subsequent to back-off and post back-off intervals. For each

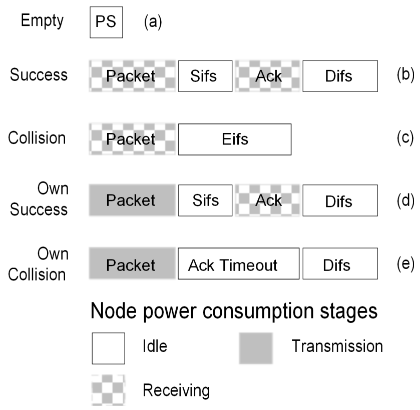

Fig. 1 Packet structure for different event types: IEEE 802.11 CSMA/CA Basic access scheme.

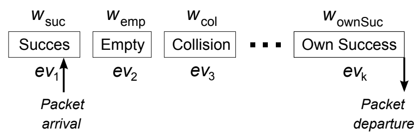

Fig. 2 Packet service time: IEEE 802.11 CSMA/CA Basic access scheme.

event type Fig. 1 color scheme represents power consumption stages that the target node traverses through during an event of the type.

The first possible case is when none of the nodes are attempting a transmission (Fig. 1(a)). Such event includes only a single Physical Slot (PS). At the end of the event nodes going through their back-off and post back-off periods, decreases their back-off counters by 1. These events are referred to as “Empty”.

Another possible case is when only one of the nodes attempts a transmission (Fig. 1(b),(d)). Since only one node transmits, the rest of the network are able to successfully decode the packet. Consequently the node that the packet is intended for, successfully receives it. The reception acknowledgment is separated from the data transmission by a SIFS interval and followed up by DIFS interval sensing carried out by all network nodes. If the transmission is performed by the target node the event is referred to as “Own Success” (Fig. 1(d)), otherwise as “Success” (Fig. 1(b)). Note that the structure of the traffic considered in this study eliminates possibility for the target node to become a data packet receiver. Meanwhile, in order to accommodate traffic a more generic structure another additional event type needs to be introduced in order to represent reception of a data packet by the target node.

Finally we consider a situation when more than one of the network nodes attempt transmitting at the same time (Fig. 1(c),(e)). In this case a number of packets are sent across the network simultaneously resulting in their collision and delivery failure. Thus, the network remainder do not receive any of these packets, but observe the channel as being busy for the duration of the transmissions. Once the transmissions are over the remainder perform EIFS interval sensing and the nodes that failed their transmission attempts wait for the acknowledgment time out. Even though the duration of the EIFS interval is preset by the manufacturer of the nodes and, thus, may vary; we assume it to be equal to the acknowledgment time-out. If the target node was one of the colliding nodes the event is referred to as “Own Collision” (Fig. 1(e)), otherwise as “Collision” (Fig. 1(c)).

In this study we assume time and energy costs associated with the back-off counter updating, packet buffer managing, and other node operations to be negligible. However those costs may become noticeable in certain cases (e.g. specific design of wireless nodes, traffic loads close to network saturation). For those cases such costs should also account for by the events as presented in [17].

3.3 Metric weights of the event types

For each packet being transmitted by a network node (the target node) this packet's MAC layer delay and transmission energy are gained from the moment of its arrival to the node's MAC layer till the moment it reaches the destination. This service time with regards to the event-based operation-time model is a sequence $\{ev_1, \ldots, ev_k\}$ of events. The sequence consists of events of “Empty”, “Success”, “Collisions” and “Own collision” types and finishes with an event of “Own success” type (Fig. 2). In case the packet have arrived during a collision or a successful transmission of another node, the first event ev_1 of the sequence is included only partially.

Each event of the $\{ev_1, \ldots, ev_k\}$ sequence has its own contribution to the values of the two metrics (e.g. energy spent by the target node, duration of the event). Consequently, each of the two metrics (delay and energy) is the sum of these contributions of the events of the sequence. In order to allow joint multi-metric analysis of the CSMA/CA mechanism, this study suggests each event type to be assigned a specific vector weight, where components of the weight reflect contribution of an event of the type to the analyzed metrics. Thus, for the joint delay and transmission energy analysis the study for each event-type i uses $w_i = (w_i^{\mathrm{T}}; w_i^{\mathrm{E}})$ vector-weights. The w_i^{E} presents energy spent by the target

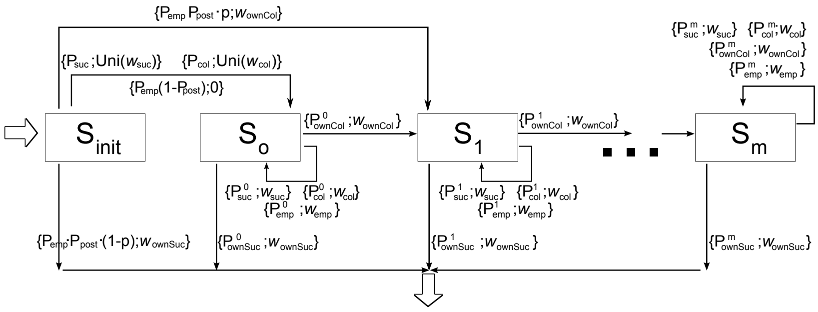

Fig. 3 Summand formation: Terminating Markov Process

node during an event of the type, and w_i^{T} component presents the time that the packet's reception was delayed by. The sum of the weights of the events of the sequence $\{ev_1, \ldots, ev_k\}$ will present a vector that contains the values of the metrics. This section presents how the components of the vector-weights are calculated in this study.

Consider an event of the "Own success" type. The acknowledgment phase of the CSMA/CA mechanism confirms to the target node the success of the most recent packet transmission. However, in case of successful delivery the packet is effectively delivered just prior to the beginning of the acknowledgment phase. Hence, duration of the acknowledgment phase should not be accounted for by the delay component $w_{\mathrm{ownSuc}}^{\mathrm{T}}$. In the case of CSMA/CA Basic access scheme (Fig. 1(d)) this weight should only account for the duration of packet transmission itself:

$$w_{\mathrm{ownSuc}}^{\mathrm{T}} = D_{\mathrm{pkt}}.$$

Meanwhile, the phase is inevitable and its energy cost should be accounted for by the $w_{\mathrm{ownSuc}}^{\mathrm{E}}$ energy component. Consider a wireless device powered by a battery of U voltage, while I_{idle}, I_{rcv} and I_{tr} are electric currents created in the device while idle, receiving and transmitting data through the channel. Consequently, the energy component of the weight for the "Own success" event type with respect to its power consumption stages (Fig. 1) is calculated as follows:

$$\begin{aligned} w_{\mathrm{ownSuc}}^{\mathrm{E}} = {} & U \cdot D_{\mathrm{pkt}} \cdot I_{\mathrm{tr}} + U \cdot D_{\mathrm{ack}} \cdot I_{\mathrm{rcv}} \\ & + U \cdot (D_{\mathrm{difs}} + D_{\mathrm{sifs}}) \cdot I_{\mathrm{idle}}. \end{aligned}$$

Consideration of the remaining event types leads to the following way for calculating the components of the vector weights:

$$\begin{aligned} w_{\mathrm{emp}}^{\mathrm{T}} &= D_{\mathrm{ps}}, \\ w_{\mathrm{emp}}^{\mathrm{E}} &= U \cdot D_{\mathrm{ps}} \cdot I_{\mathrm{idle}}, \\ w_{\mathrm{suc}}^{\mathrm{T}} &= D_{\mathrm{pkt}} + D_{\mathrm{sifs}} + D_{\mathrm{ack}} + D_{\mathrm{difs}}, \\ w_{\mathrm{suc}}^{\mathrm{E}} &= U \cdot (D_{\mathrm{pkt}} + D_{\mathrm{ack}}) \cdot I_{\mathrm{rcv}} \\ &\quad + U \cdot (D_{\mathrm{difs}} + D_{\mathrm{sifs}}) \cdot I_{\mathrm{idle}}, \\ w_{\mathrm{col}}^{\mathrm{T}} &= D_{\mathrm{pkt}} + D_{\mathrm{eifs}}, \\ w_{\mathrm{col}}^{\mathrm{E}} &= U \cdot (D_{\mathrm{pkt}} \cdot I_{\mathrm{rcv}} + D_{\mathrm{difs}} \cdot I_{\mathrm{idle}}), \\ w_{\mathrm{ownCol}}^{\mathrm{T}} &= D_{\mathrm{pkt}} + D_{\mathrm{ackTimeOut}} + D_{\mathrm{difs}}, \\ w_{\mathrm{ownCol}}^{\mathrm{E}} &= U \cdot D_{\mathrm{pkt}} \cdot I_{\mathrm{tr}} \\ &\quad + U \cdot (D_{\mathrm{ackTimeOut}} + D_{\mathrm{difs}}) \cdot I_{\mathrm{idle}}. \end{aligned}$$

4 Random sum model

For a generic packet this study suggests a random sum model S for the two analyzed metrics. The summands of the model are the two-dimensional w_{emp}, w_{suc}, w_{col}, w_{ownSuc}, w_{ownCol} weights presented in Section 3.3. The summand formation is described by a Terminating Markov Process, which is presented by a diagram pictured on Fig. 3. The diagram states are denoted by S_{int}, S_0, ..., S_m squares, where S_{int} represents possible transmissions of the target node being in the post back-off stage, and S_i for $i \in [0; m]$ represents transmissions of the i^{th} back-off stage. The arrows of two types are used on the figure: wide arrows mark the initial state of the process and the termination point, the remaining arrows show state transition of the process. Each state transition arrow is accompanied with a number of duplexes framed in brackets. Each duplex indicates probability of the state transition and the summand generated by the transition. Initially the process enters the S_{init} state and it corresponds to 0 initial sum; the resultant sum is obtained during probabilistic transitions of the process till the moment it reaches the termination point. State-transition probabilities encapsulate the influence of the transmission processes of the neighboring nodes.

These probabilities are calculated via τ and P_{post} probabilities. τ is a probability for generic node to attempt transmission as part of a generic event, and P_{post} is a probability for a generic node to have completed its post back off stage prior to a packet arrival. Probabilities τ and P_{post} are calculated via a so-called basis model that describes behavior of a generic wireless network node. Although any existing model that allows estimating the probability could be used as the basis model, this study uses the model presented by Qi et al. [10]. The model presents a two-dimensional Markov-chain that describes the state-transitioning process for a generic wireless node, and while τ is a product of the analysis presented in [10], P_{post} corresponds to the stationary probability for the Markov-chain to be at the $(0;0)_{\text{e}}$ stage.

4.1 Initial state

Under non-saturated traffic conditions a node that has no further packets enters a so-called post back-off period. Successful accomplishment of the period allows the node to proceed immediately with the next packet transmission without engaging full CSMA/CA mechanism if the wireless media is not used by any of the other nodes. These cases are considered in the S_{int} state.

Prior to a next packet arrival the target node being at the post back-off stage does not contend for the media access. Hence, knowing τ probability and total amount of network nodes n, a generic event in this case could be of "Empty", "Success", "Collisions" types with probabilities calculated for the $n-1$ contending nodes (all but the target node) in the following way:

$$\begin{aligned}
P_0 &= (1-\tau)^{n-1},\\
P_1 &= (n-1)\cdot\tau\cdot(1-\tau)^{n-2},\\
P_{\geq 2} &= 1-(1+(n-2)\tau)\cdot(1-\tau)^{n-2}.
\end{aligned}$$

Knowing time durations of the events allows calculating an expectation for duration of a generic event $E(x)$ in the considered case. And as packet arrival process is Poisson, then due to the PASTA (Poisson Arrivals See Time Averages) property, probabilities of a packet arriving during an event of one of the types are calculated as follows:

$$\begin{aligned}
E(x) &= P_0\cdot D_{\text{emp}} + P_1\cdot D_{\text{suc}} + P_{\geq 2}\cdot D_{\text{col}},\\
P_{\text{emp}} &= P_0\cdot D_{\text{emp}}/E(x),\\
P_{\text{suc}} &= P_1\cdot D_{\text{suc}}/E(x),\\
P_{\text{col}} &= P_{\geq 2}\cdot D_{\text{col}}/E(x).
\end{aligned}$$

Thus, with probabilities P_{suc} and P_{col} a new packet arrives at the target node during a collision or a successful transmission of its neighbors. In that case the target node is required to hold off till the end of the neighbors' attempt and proceed to the 0 back-off stage. Also, applying the PASTA, the arrival point is uniformly distributed across the event's duration. This corresponds to the transition to the S_0 state with $Uni(w_{\text{suc}})$ and $Uni(w_{\text{col}})$ summands generation.

With probability P_{emp} a new arrival happens while no other nodes attempt transmitting. If the target node has its post back-off interval completed (probability P_{post} from the basic model) it attempts to transmit immediately. However, the media is observed to be free by the rest of the nodes also, which attempt to transmit with probability $p = 1 - P_0$. As a result the target node meets collision and moves to the 1 back-off stage, which corresponds to the transition to the S_1 generating w_{ownCol} summand. With $1-p$ probability the nodes remain quiet, which results into the target node's successful transmission. This is presented on the diagram by the transition to the termination state. With $1 - P_{\text{post}}$ probability the target node does not have its post back-off completed at the new packet arrival time. In that case the remaining post back-off becomes its 0 back-off stage period. And that corresponds to the transition to the S_0 state generating 0 summand.

4.2 Back-off stage i

As at the i^{th} stage back-off interval duration is selected randomly from the available back-off window $(2^i\cdot W)$, transmission attempt probability for the target node is set to $\tau_i = 1/(2^i\cdot W)$. Therefore probabilities for the target node to encounter an event of any of the types are the following:

$$\begin{aligned}
P^i_{\text{emp}} &= P_0\cdot(1-\tau_i),\\
P^i_{\text{suc}} &= P_1\cdot(1-\tau_i),\\
P^i_{\text{col}} &= P_{\geq 2}\cdot(1-\tau_i),\\
P^i_{\text{ownSuc}} &= P_0\cdot\tau_i,\\
P^i_{\text{ownCol}} &= (P_{\geq 2}+P_1)\cdot\tau_i.
\end{aligned}$$

Each encounter triggers a state transition that generates a summand of the encounter's weight. Thus, encountering an "Own Collision" event triggers transition to the state representing the next back-off stage unless the process has previously reached its maximal back-off stage state S_m. Encountering an "Own Success" event triggers the transition to the termination state. Transitions triggered by "Empty", "Collision" and "Success" events encountering leave the process in the same state.

5 Numerical computation

While for the two analyzed metrics the previous section presents its internal structure as a random sum S of

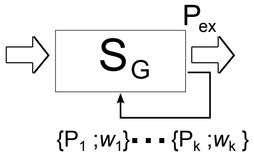

Fig. 4 Generalized back-off Stage S_{G}: random sum formation process.

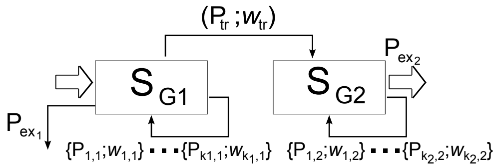

Fig. 5 Two consecutive generalized back-off stages: random sum formation.

specific vector weights, this section provides numerical analysis of the sum. The analysis is carried out via the apparatus of characteristic functions. First we obtain a characteristic function for a random sub-sum generated by the Terminating Markov Process while at a single back-off stage. Then we obtain a characteristic function for a sub-sum generated while transitioning through a number of consecutive back-off stages by using their individual characteristic functions. This enables us to obtain the characteristic function of the entire Random Sum model. This function is further used to numerically obtain the sought distribution.

5.1 Individual Back-off Stage

Consider one of the back-off stages of the Terminating Markov Process and a sub-sum of the sum S that includes only summands generated by the process being at this stage. Summand formation of the sub-sum may be described by the the generalized stage process S_{G} presented on Fig. 4. Summands of k types with weights $w_1, \ldots, w_k$ are generated with probabilities $p_1, \ldots, p_k$ correspondingly; while with the probability

$$p_{\text{ex}} = 1 - \sum_{l=0}^{k} p_l$$

the summand formation is terminated. The generalized stage process presents a template for the individual back-off stages of the overall Terminating Markov Process. So, for $\forall j \in [0; m-1]$ choosing k equal 3, and P^j_{suc}, P^j_{col}, P^j_{emp} for weights w_{suc}, w_{col}, w_{emp} will give the S_j stage. Similarly, choosing $k = 4$, and P^m_{suc}, P^m_{col}, P^m_{emp}, P^m_{ownCol} for weights w_{suc}, w_{col}, w_{emp}, w_{ownCol} will give the final S_m stage. Termination of an individual back-off stage processes corresponds to the overall process termination or transition to the next back-off stage if such a stage exists.

Consider the sub-sum generated by the generalized stage process. For each $l \geq 0$ this sub-sum includes exactly l summands with probability

$$p_l = p_{\text{ex}} \cdot (1 - p_{\text{ex}})^l. \tag{1}$$

Meanwhile, each of the l summands equals $w_1, \ldots, w_k$ with probabilities $p_1/(1 - p_{\text{ex}}), \ldots, p_k/(1 - p_{\text{ex}})$ correspondingly and therefore has the following characteristic function:

$$\varphi(t) = \frac{1}{(1 - p_{\text{ex}})} \cdot \sum_{l=1}^{k} p_l \cdot e^{i \cdot w_l \cdot t}. \tag{2}$$

Therefore, characteristic function for the sub-sum of exactly l summands equals $\varphi(t)^l$. This, in turn, together with Eq. 1 allow calculating characteristic function for the entire sub-sum S_{G} in the following way:

$$\varphi_{S_{\text{G}}}(t) = p_{\text{ex}} \cdot \sum_{l=0}^{\infty} \left((1 - p_{\text{ex}}) \cdot \varphi(t)\right)^l. \tag{3}$$

Part of the right side of Eq. 3 is easily recognized as the sum of the geometric progression. Consequently Eq. 3 reduces to the following:

$$\varphi_{S_{\text{G}}}(t) = p_{\text{ex}} / (1 - \sum_{l=1}^{k} p_l \cdot e^{i \cdot w_l \cdot t}). \tag{4}$$

Eq. 4 for any back-off stage of the overall Terminating Markov Process presents the characteristic function for the sub-sum of the sum S that includes only summands generated by the process at this stage.

5.2 Consecutive Back-off Stages

Consider a sub-sum that includes only summands generated by the Terminating Markov Process while transitioning through a pair of consecutive back-off stages $S_{\text{G1}} \to S_{\text{G2}}$ interconnected as presented on Fig. 5. Similar to the previous sub-section each of the stages is represented as a generalized stage process. The summand formation is terminated at the S_{G1} and S_{G2} stages with probabilities P_{ex_1} and P_{ex_2} correspondingly. With probability P_{tr} the summand generation process switches from the initial S_{G1} stage to the S_{G2}, where summand w_{tr} is generated during the switching. It is easy to show that with the probability

$$p_{\text{sg}_1} = \frac{P_{\text{ex}_1}}{P_{\text{tr}} + P_{\text{ex}_1}} \tag{5}$$

the sub-sum consists of only summands generated at the S_{G1} stage. Therefore, Eq. 5 together with $\varphi_{\text{sg}_1}(t)$ and $\varphi_{\text{sg}_2}(t)$ (obtained as presented by Eq. 4) result in the characteristic function for the two consecutive stages being obtained as follows:

$$\varphi_{\mathrm{sg_1\to sg_2}}(t) = (1-p_{\mathrm{sg_1}})\cdot\varphi_{\mathrm{sg_1}}(t)\cdot e^{i\cdot w_{tr}\cdot t}\cdot\varphi_{\mathrm{sg_2}}(t) + p_{\mathrm{sg_1}}\cdot\varphi_{\mathrm{sg_1}}(t). \quad (6)$$

Going back to the overall process Fig. 3 for $\forall j \le m-1$ the probability of transitioning from stage S_j to stage S_{j+1} equals P^i_{ownCol}, while probability for transitioning to the termination state equals to P^i_{ownSuc}. Therefore, taking into consideration values of the two probabilities from Section 4.2 we transform Eq. 6 to the following:

$$\varphi_{\mathrm{s_j\to s_{j+1}}}(t) = (1-P_0)\cdot\varphi_{\mathrm{s_j}}(t)\cdot e^{i\cdot w_{\mathrm{ownCol}}\cdot t}\cdot\varphi_{\mathrm{s_{j+1}}}(t) + P_0\cdot\varphi_{\mathrm{s_j}}(t). \quad (7)$$

Similar consideration leads to Alg. 1 that calculates for a particular t the value of the characteristic function $\varphi_{\mathrm{s_l\to s_m}}(t)$ for $S_l \to S_m$ consecutive stages, where S_m is the maximal back-off stage and $l \in [0; m-1]$. The calculation uses a buffer-variable $\widetilde{\varphi}$. Note that the calculation as well as Eq. 7 and Eq. 4 do not take into consideration weights gained during transitioning to the termination stage of the process, while these weights equal to w_{ownSuc}. These weights will be accounted for in the next subsection, where we consider the characteristic function for the entire random sum.

Algorithm 1 Calculation of the $\varphi_{\mathrm{s_l\to s_m}}(t)$ value for any particular t of the characteristic function for $S_l \to S_m$ consecutive back-off stages ($l \in [0; m-1]$).

Calculate $\varphi_{\mathrm{s_l}}(t)$
$\widetilde{\varphi} = \varphi_{\mathrm{s_l}}(t)$
$\varphi_{\mathrm{s_l\to s_m}}(t) = 0$
for $j = l+1 \to m-1$ **do**
  Calculate $\varphi_{\mathrm{s_j}}(t)$
  $\varphi_{\mathrm{s_l\to s_m}}(t) += P_0\cdot\widetilde{\varphi}$
  $\widetilde{\varphi} = (1-P_0)\cdot\widetilde{\varphi}\cdot e^{i\cdot w_{\mathrm{ownCol}}\cdot t}\cdot\varphi_{\mathrm{s_j}}(t)$
end for
Calculate $\varphi_{\mathrm{s_m}}(t)$
$\varphi_{\mathrm{s_l\to s_m}}(t) += P_0\cdot\widetilde{\varphi}$
$\varphi_{\mathrm{s_l\to s_m}}(t) += (P_1+P_{\ge 2})\cdot\widetilde{\varphi}\cdot e^{i\cdot w_{\mathrm{ownCol}}\cdot t}\cdot\varphi_{\mathrm{s_m}}(t)$
return $\varphi_{\mathrm{s_l\to s_m}}(t)$

5.3 Entire model

Results of the previous section allow to calculate values of characteristic functions $\varphi_{\mathrm{s_0\to s_m}}(t)$ and $\varphi_{\mathrm{s_1\to s_m}}(t)$ for two random sub-sums which include summands generated by the process while traversing through $0 \to m$ and $1 \to m$ consecutive back-off stages correspondingly. The sub-sums are the core of the entire random sum model, whereas the model is a probabilistic mixture their convolutions with either uniform random variables ($Uni(w)$) or constants. Therefore, Alg. 2 presents a pseudo-code that calculates for a particular t the value of the characteristic function $\varphi_{\mathrm{s}}(t)$ of the entire random sum model. Note that the final line of the pseudo-code accounts for summands generated in result of transitioning to the termination state.

Algorithm 2 $\varphi_{\mathrm{s}}(t)$ value of the characteristic function of the complete random sum model (Fig. 3).

Calculate $\varphi_{\mathrm{s_0\to s_m}}(t)$
Calculate $\varphi_{\mathrm{s_1\to s_m}}(t)$
$\varphi_{\mathrm{s}}(t) = P_{\mathrm{suc}}\cdot\varphi_{\mathrm{s_0\to s_m}}(t)\cdot(e^{i\cdot w_{\mathrm{suc}}\cdot t}-1)/(i\cdot t\cdot w_{\mathrm{suc}})$
$\varphi_{\mathrm{s}}(t) += P_{\mathrm{col}}\cdot\varphi_{\mathrm{s_0\to s_m}}(t)\cdot(e^{i\cdot w_{\mathrm{col}}\cdot t}-1)/(i\cdot t\cdot w_{\mathrm{col}})$
$\varphi_{\mathrm{s}}(t) += P_{\mathrm{emp}}\cdot(1-P_{\mathrm{post}})\cdot\varphi_{\mathrm{s_0\to s_m}}(t)$
$\varphi_{\mathrm{s}}(t) += P_{\mathrm{emp}}\cdot P_{\mathrm{post}}\cdot(1-P_0)\cdot\varphi_{\mathrm{s_1\to s_m}}(t)\cdot e^{i\cdot w_{\mathrm{ownCol}}\cdot t}$
$\varphi_{\mathrm{s}}(t) += P_{\mathrm{emp}}\cdot P_{\mathrm{post}}\cdot P_0$
$\varphi_{\mathrm{s}}(t) = \varphi_{\mathrm{s}}(t) * e^{i\cdot w_{\mathrm{ownSuc}}\cdot t}$
return $\varphi_{\mathrm{s}}(t)$

5.4 Deriving the distribution

The apparatus of characteristic functions is a powerful tool that is commonly used in modeling. Knowing for a certain random variable ξ its characteristic function φ_ξ provides all necessary information about the variable, whereas deriving Cumulative Distribution Function ($F(x) = P(\xi \le x)$), histogram and others becomes only the matter of Inverse Fourier Transformation of φ_ξ. Therefore, coming back to the proposed random sum model the probability $P(a; b)$ that for a generic data packet the delay $D \in (a_1; b_1)$ and transmission energy $E \in (a_2; b_2)$ equals [21]:

$$\lim_{L_1\to\infty}\lim_{L_2\to\infty}\int_{-L_1}^{L_1}\int_{-L_2}^{L_2}\Big(\prod_{k=1}^{2}\frac{e^{-i\cdot x_k\cdot a_k}-e^{-i\cdot x_k\cdot b_k}}{2\cdot\pi\cdot i\cdot x_k}\Big)\cdot\varphi_S(x)\cdot dx_1 dx_2, \quad (8)$$

Eq. 8 together with Alg. 2 allow numerically calculate the probability $P(a; b)$, where for this calculation the study uses functionality of the MATLAB computing environment. Meanwhile, ability to calculate such $P(a; b)$ probabilities allows obtaining the sought joint distribution in the form of histogram.

6 Model evaluation

In order to validate the proposed approach this section presents a comparison of NS3-based simulation results [22] with prediction of the proposed model. As the proposed model focuses on the delay and transmission energy gained at the MAC layer through the use of the CSMA/CA mechanism, the evaluation does not include delay and energy costs that appear at other

Table 1 Parameter values for model and simulations

Sifs	10 us	Difs	50 us
Ph.slot(σ)	20 us	ACK	304 us
PKT	966 us	Rate	11 Mbps
TX	17.4 mA	RX	19.4 mA
Idle	426 uA	W_0	31

Table 2 Metric weights of the event types

$w^{\mathrm{T}}_{\mathrm{emp}}$	20 us	$w^{\mathrm{E}}_{\mathrm{emp}}$	0.02556 uJ
$w^{\mathrm{T}}_{\mathrm{suc}}$	1330 us	$w^{\mathrm{E}}_{\mathrm{suc}}$	73.991 uJ
$w^{\mathrm{T}}_{\mathrm{col}}$	1330 us	$w^{\mathrm{E}}_{\mathrm{col}}$	56.686 uJ
$w^{\mathrm{T}}_{\mathrm{ownSuc}}$	966 us	$w^{\mathrm{E}}_{\mathrm{ownSuc}}$	50.425 uJ
$w^{\mathrm{T}}_{\mathrm{ownCol}}$	1330 us	$w^{\mathrm{E}}_{\mathrm{ownCol}}$	50.0890 uJ

layers (e.g. queuing delay, energy spent on packet processing). Single-hop wireless networks of one gateway and 12 homogeneous IEEE 802.11b nodes operating under normalized traffic loads varying from 0.1 to 0.4 are chosen for the comparison. Each network node transmits packets of 1Kb through 11Mbps wireless channel and exploits Basic access scheme. Each wireless node is equipped with a battery of 3V voltage, while devices electric currents for signal transmission, reception, idle and sleep states are correspondingly 17.4, 19.4, 0.425 0.02 mA. Remaining simulation parameters are gathered in Tab. 1. Interval weights calculated for the simulation scenario are accumulated in Tab. 2. In this evaluation for each packet we measure its transmission energy at the moment of its successful reception by the gateway. Therefore, the $w^{\mathrm{E}}_{\mathrm{ownSuc}}$ only accounts for the energy spent on the actual transmission of the packet. Even though this allows evaluating performance quality of the model, however analysis of real wireless networks will require using the weights as in Section 3.3.

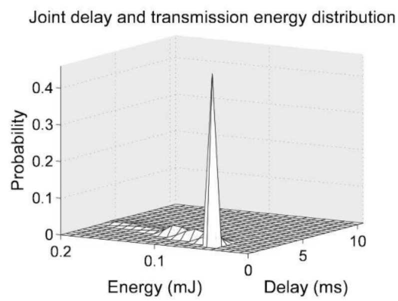

Fig. 6 Evaluation: IEEE 802.11b, 12 nodes, 1Kb/packet, 11Mbps/channel, Load 0.4.

Numerical analysis of the the random sum model for weights reflecting MAC layer packet delay and transmission energy metrics simultaneously allows estimating their joint distribution for a generic packet. Such distribution for normalized network load of 0.4 is presented on Fig. 6. Noticeable peak at (1ms; 0.05mJ) corresponds to successful post back-off transmission attempts and emphasizes necessity of precise post back-off modeling by the basis model. The remaining graph presents successes of the other back-off stages. Shape of the graph suggests of a correlation between values of the two analyzed metrics.

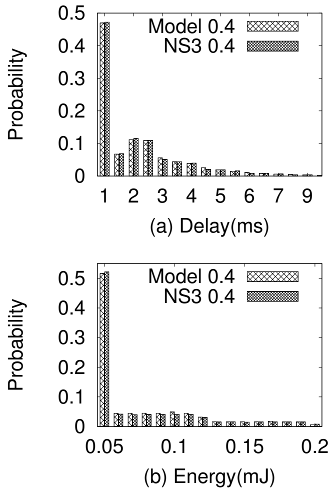

Fig. 7 Evaluation: IEEE 802.11b, 12 nodes, 1Kb/packet, 11Mbps/channel, Load 0.4: (a) Packet delay and (b) transmission energy distributions.

Further we present model prediction validation carried out separately for each metrics. Hence, Fig. 7 (a) and (b) present distributions of MAC layer packet delay and transmission energy. As well as on Fig. 6 peaks at 1ms and 0.05 mJ correspond to the successful post back-off attempts.

Fig. 8 (a) and (b) present Tail Distribution (TD) functions for both transmission delay and energy for normalized traffic load varying from 0.1 to 0.4 values. TD functions of higher loads have higher values for the same delay and energy boundaries as expected. This is explained by the fact that in case of higher load necessity for each node to compete with its neighbors for physical media access growth, which results in the transmission delay and energy increase. Graphics of TD functions presented on the figures are of exponential nature. This agrees with results of Ivanov et al. [20] where

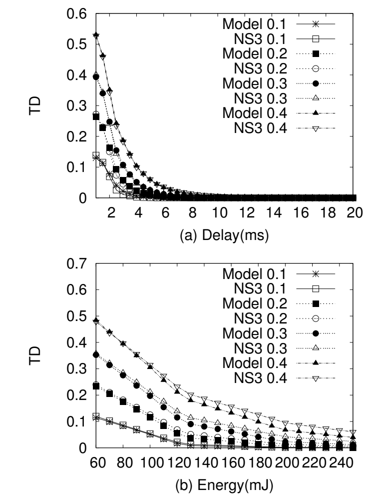

Fig. 8 Evaluation: IEEE 802.11b, 12 nodes, 1Kb/packet, 11Mbps/channel, Load 0.4: (a) Packet delay and (b) transmission energy TD.

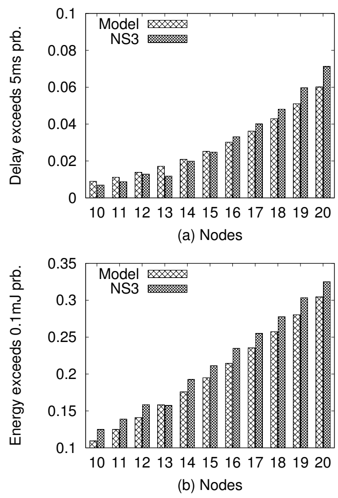

Fig. 10 Evaluation: IEEE 802.11b, from 10 to 20 nodes, 1Kb/packet, 11Mbps/channel, overall load varies from 0.1 to 0.2: (a) packet delay exceeds 5ms and (b) transmission energy exceeds 0.1mJ

an exponential estimation of delay distribution is presented but only for saturated traffic scenarios.

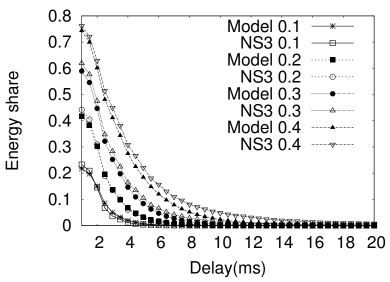

Fig. 9 Evaluation: IEEE 802.11b, 12 nodes, 1Kb/packet, 11Mbps/channel: Energy share.

Finally, Fig. 9 reflects on the energy shares spent on data transmissions which duration exceeds certain values. Results of Fig. 9 are directly derived from joint distributions from normalized load varying from 0.1 to 0.4. Such a figure together with Fig. 8 (a) allows, for example, optimizing energy expenditure by tightening the delivery timeout in such a way that QoS will still remain satisfactory.

Fig. 10 presents results obtained for single-hop networks of various sizes. The considered case includes networks of 10 to 20 nodes. Each individual node transmits at 100 Kbps rate, which results in the overall load varying from 0.1 to 0.2. In this case load of larger networks is higher, and this results in longer delay and higher energy expenditure of performed transmissions. Thus, Fig. 10 presents probability for a generic packet to overstay 5ms timeout and Fig. 10(b) presents probability for a transmission to pass energy expenditure mark of 0.1mJ.

As it can be seen from the picture, presented results of the proposed model show good agreement with the results of NS3 simulation for so-called average and low loads. However, prediction precision worsens with a normalized network load increase. This happens due to the influence of packet buffering on the network performance, which is neglected by the exploited basis model and becomes noticeable for higher loads. So, the basis model should reflect packet buffering in addition to the mentioned earlier necessity of precise post back-off modeling. Yet, no such model is known to the authors, as models considering packet buffering (Liu et al. [12] for example) neglect post back-off states modeling and vice-versa.

7 Conclusions

Packet delay and transmission energy analysis are important for green IEEE 802.11 wireless networks engineering. For the purpose of modeling we have presented overall network operational time as a sequences of events of “Empty”, “Success”, “Collision”, “Own success” and “Own collision” types. The two considered metrics have been presented as weights associated with these even types. Basing on this representation we have proposed a random sum model that allows approximating numerically distributions of values for both metrics together with their joint distribution. We also have presented an algorithm of such an approximation. Precision of the approximation has been validated against NS3-based simulation, and the model has been seen to capture various features of the wireless network operation. These features include probability density peak corresponding to successful transmissions of the post-back stage, dependence between the two metrics, growth in delay and energy expenditure caused by the network load increase, exponential nature of Tail Distributions of the metrics.

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